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# Laboratory evidence for proton energization by collisionless shock surfing

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The origin of the high-energy particles flying through the Universe is still an open question<sup>1</sup>. One identified source is collisionless shock waves formed when energy release from stars encounters the tenuous magnetized space environment<sup>2,3</sup>. By interacting with the ambient medium, these shocks can transfer energy to particles, thus accelerating them<sup>4,5</sup>. Characterization of these shocks has become very rich with satellite measurements at the Earth’s bow shock and powerful numerical simulations, however identifying the exact mechanism, or combination of mechanisms enabling particle acceleration is still widely debated<sup>1,3,6-8</sup>. Here we show that astrophysically relevant super-critical quasi-perpendicular magnetized collisionless shocks can be produced and characterized in the laboratory. Moreover, we observe a “foot” in the shock profile that is characteristic of super-critical shocks as well as the energization of protons picked up from the ambient gas to hundred keV. Our kinetic particle-in-cell simulations modeling of our laboratory event identified shock surfing<sup>9,10</sup> as the proton acceleration mechanism. Our observations not only provide the first direct evidence of early stage ion energization by collisionless shocks, but they also highlight the role this particular mechanism plays in energizing ambient ions to feed further stages of acceleration<sup>11</sup>. Furthermore, our results also open the door to future laboratory experiments investigating the possible transition to other mechanisms, when increasing the magnetic field strength, or the effect induced shock front ripples<sup>12,13</sup> could have on acceleration processes.

The acceleration of energetic charged particles by collisionless shock waves is an ubiquitous phenomenon in

astrophysical environments, e.g. during the expansion of supernova remnants (SNRs) in the interstellar medium (ISM)<sup>14</sup>, during solar wind interaction with the Earth’s magnetosphere<sup>15</sup>, or with the ISM (at the so-called termination shock)<sup>16</sup>. In SNRs, there is a growing consensus that the acceleration is efficient at quasi-parallel shocks<sup>17,18</sup>, while in interplanetary shocks, the quasi-perpendicular scenario (i.e. the magnetic field is perpendicular to the shock normal, or the on-axis shock propagation direction) is invoked<sup>13,19,20</sup>. The quasi-perpendicular shocks that produce particle acceleration are qualified as super-critical; they have a specific characteristic such that in addition to dissipation by thermalization and entropy, energy is dissipated also by reflecting the upstream plasma. According to<sup>21,22</sup>, the threshold for the super-critical regime of the quasi-perpendicular shock is defined as:  $M_{ms} = v_{sh}/\sqrt{v_A^2 + C_s^2} \gtrsim 2.7$  (where  $M_{ms}$  is the magnetosonic Mach number,  $v_{sh}$ ,  $v_A$  and  $C_s$  are the shock, Alfvénic and sound velocity, respectively).

Three basic ion acceleration mechanisms are commonly considered to be induced by such shocks<sup>3,4,6</sup>: diffusive shock acceleration (DSA), shock surfing acceleration (SSA), and shock drift acceleration (SDA). The first proceeds with particles gaining energy by scattering off magnetic perturbations present in the shock upstream and downstream media, whereas, in SSA and SDA, the particles gyro-rotate (Larmor motion) in close proximity with the shock and gain energy through the induced electric field associated with the shock.

These last two processes are mostly differentiated by how and where the particles are trapped around the shock front and the ratio of the ion Larmor radius vs. the shock width (large for SSA and small for SDA)<sup>10,12</sup>. And here in our case we expect that SSA dominates over SDA, as will be detailed below.

94 DSA, which is commonly invoked for high-energy particle  
 95 acceleration in SNRs, is thought to require quite  
 96 energetic particles to be effective<sup>9,23</sup>, which raises the  
 97 so-called “injection problem” of their generation<sup>24</sup>. Pro-  
 98 viding those pre-accelerated seed particles is precisely  
 99 thought to be accomplished by SSA or SDA, which are  
 100 evoked to accelerate particle at low energies, e.g. in our  
 101 solar system<sup>19</sup>.

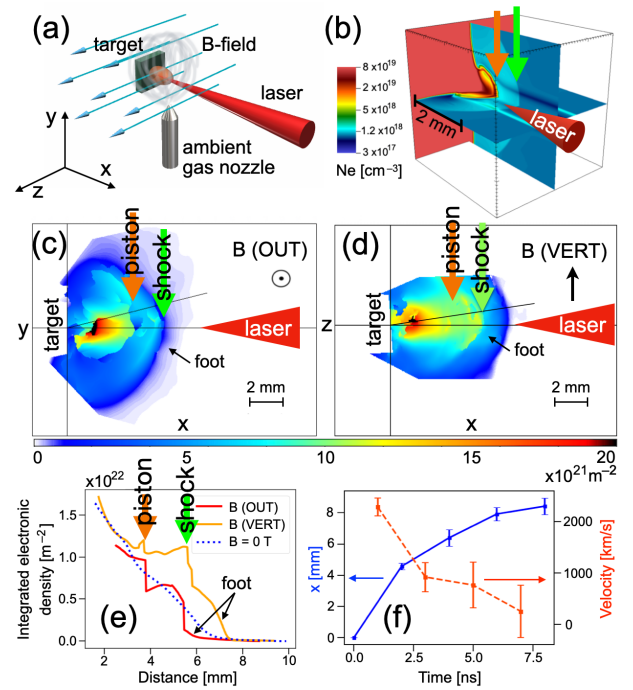
102 Due to the small sampling of such phenomena even  
 103 close to Earth, the complexity of the structuring of such  
 104 shocks<sup>9,25</sup>, and the related difficulty in modelling them  
 105 realistically, the question of the effectiveness and relative  
 106 importance of SDA and SSA<sup>12</sup> is still largely debated in  
 107 the literature.

108 We will first show that laboratory experiments can be  
 109 performed to generate and characterize globally mildly  
 110 super-critical, quasi-perpendicular magnetized collision-  
 111 less shocks. The shock shown in Fig. 1 is typically pro-  
 112 duced by using a laser-driven piston to send an expanding  
 113 plasma into an ambient (a cloud of hydrogen) secondary  
 114 plasma<sup>26</sup> in an externally controlled, homogeneous and  
 115 highly reproducible magnetic field (see Methods). The  
 116 high-strength applied magnetic field<sup>27</sup> we use is key in  
 117 order to ensure the collisionless nature of the induced  
 118 shock. The key parameters of the laboratory created  
 119 shock are summarized in Table 1, which shows that they  
 120 compare favorably with the parameters of the Earth’s  
 121 bow shock<sup>15,28</sup>, the solar wind termination shock<sup>16,29,30</sup>,  
 122 and of four different non-relativistic SNRs interacting  
 123 with dense molecular clouds (see Extended Data Table 1  
 124 detailing the considered objects).

|                             | $M_{ms}$   | $\lambda_{mfp}/r_{L,i}$ |
|-----------------------------|------------|-------------------------|
| <b>Our experiment</b>       | 3.1        | 12.2                    |
| <b>Bow Shock</b>            | 2.8        | $1.2 \times 10^8$       |
| <b>Term. Shock</b>          | 4.9        | $7.4 \times 10^7$       |
| <b>Mixed-morphology SNR</b> | $\geq 3.2$ | $\geq 2.0 \times 10^2$  |

153 **Table 1. Parameters of the laboratory shocks as well**  
 154 **as that of three shocks found in natural events.** The  
 155 listed parameters for each plasma are: the Magnetosonic  
 156 Mach number ( $M_{ms}$ , see text), and the ratio of the colli-  
 157 sional mean free path ( $\lambda_{mfp}$ ) over the ion Larmor radius  
 158 ( $r_{L,i}$ ). The first shows that all shocks are super-critical, the  
 159 second shows that all shocks are collisionless, i.e. electromag-  
 160 netic forces dominate over collisions since the collision mean  
 161 free path is always much larger than the ion Larmor radius.  
 162 The three natural events are: the Earth’s bow shock, the so-  
 163 lar wind termination shock, and low-velocity interactions of  
 164 mixed-morphology SNRs with dense molecular clouds. De-  
 165 tails on the parameters and how they are derived are given in  
 166 Extended Data Table 1.

167 A snapshot of the integrated plasma electron density  
 168 was obtained by optical probing at 4 ns after the laser  
 169 irradiation of the target and is shown in Fig. 1c and d in  
 170 the two perpendicular planes containing the main expan-  
 171 sion axis. The laser comes from the right side and the  
 172 piston source target is located at the left (at  $x = 0$ ). We



125

126 **Figure 1. Configuration and characterization of the**  
 127 **laboratory super-critical shock.** (a) Cartoon of the setup  
 128 of the experiment performed at JLF/Titan to characterize the  
 129 shock. (b) Three-dimensional (3D) rendering of the ablated  
 130 piston interacting with the magnetized ambient gas at 4 ns  
 131 from the FLASH simulation (see Methods). The orange ar-  
 132 row represents the piston front, while the green one the shock  
 133 front. (c) and (d) Experimental density measurement (inte-  
 134 grated along the line of sight) 4 ns after the laser irradiation  
 135 of the solid target (at  $t = 0$ ) recorded in the two different and  
 136 complementary xy and xz planes in order to characterize in  
 137 three-dimensions the overall plasma. Each image corresponds  
 138 to a different laser shot. More images at different times are  
 139 shown in Extended Data Fig. 1. (e) Lineouts obtained from  
 140 the images above, showing the integrated density along the  
 141 black solid lines starting from the targets. (f) Evolution of  
 142 the shock front position along the x-axis, and the correspon-  
 143 ding velocity. Each point corresponds to the average of the  
 144 shock front of all relevant shots. The error bars on the x po-  
 145 sition represent not only the maximum extent of the variation  
 146 of the shock front position as observed in relevant shots, but  
 147 they also integrate the uncertainty of the initial target sur-  
 148 face ( $x = 0$ ) as well as the width of the shock front. The  
 149 error bars on the velocity correspond to the propagation of  
 150 the errors on the position. The small relative error attests to  
 151 the reproducibility of the overall experimental phenomenon.

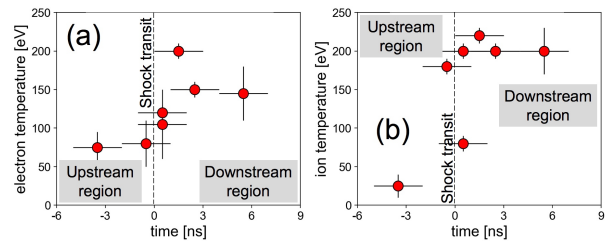
173 can clearly see both the piston front and the shock front  
 174 (indicated by the orange and green arrows, respectively).  
 175 A lineout of the plasma density is shown in Fig. 1e, where  
 176 the piston and shock fronts are well identified by the  
 177 abrupt density changes. The piston front is steepened  
 178 by the compression induced by the magnetic field<sup>31</sup> (see  
 179 also Extended Data Fig. 2). In contrast, when the B-  
 180 field is switched off, only a smooth plasma expansion into  
 181 the ambient gas (blue dashed line) can be seen. In the

182 case when the magnetic field is applied, another clear  
 183 signature of the magnetized shock, as observed by satel-  
 184 lites crossing the Earth’s bow shock<sup>32</sup>, is the noticeable  
 185 feature of a “foot” in the density profile, located in the  
 186 shock upstream (US). It is due to the cyclic evolution  
 187 of the plasma: the plasma in the foot is picked up to  
 188 form the shock front, while the front itself is also peri-  
 189 odically dismantled by the Larmor motion of the ions.  
 190 The observed foot width is of the order 0.5-1 mm, which  
 191 compares favourably with the expected foot width being  
 192 twice the ion inertial length<sup>33</sup> (which is here  $\approx 0.23$   
 193 mm), and with the width observed in our simulations  
 194 shown below.

195 Fig. 1f shows the shock front position evolution and  
 196 the corresponding velocity deduced from it, which shows  
 197 the very fast decrease of the shock velocity over the first  
 198 few ns. Before 2.6 ns, the shock front velocity is around  
 199  $V_0 = 1500$  km/s, corresponding to an ion-ion collisional  
 200 mean-free-path  $\lambda_{mfp} = V_0\tau_i \approx 10$  mm, with the ion col-  
 201 lisional time  $\tau_i \approx 6$  ns – both are larger than the inter-  
 202 action spatial and temporal scales, indicating that the  
 203 shock is collisionless. Note also that for such velocity,  
 204 the Larmor radius of the ions in the shock is around 0.8  
 205 mm, i.e. larger than the shock width, which, although  
 206 it is too small to be well resolved by our interferometer,  
 207 is well below 0.2 mm, suggesting favourable conditions  
 208 for SSA to be at play. However, after 4-5 ns, the shock  
 209 velocity decreases rapidly to about 500 km/s, thus be-  
 210 coming sub-critical and the foot of the shock becomes  
 211 less distinguishable (see also in Extended Data Fig. 1).  
 212 Later we will demonstrate, with the help of kinetic simu-  
 213 lations, that the proton acceleration happens within the  
 214 first 2-3 ns of the shock evolution, i.e. when the shock is  
 215 super-critical, with a front velocity above 1000 km/s.

235 The plasma temperature was measured at a fixed loca-  
 236 tion at different instants in time (see Methods), allowing  
 237 to characterize the temperature increase in the shock as  
 238 it swept through the probed volume, as shown in Fig.  
 239 2. Before the shock front, the electron temperature  $T_e$   
 240 is around 70 eV and ion temperature  $T_i$  is about 20 eV.  
 241 While behind the shock front,  $T_e$  is almost doubled (see  
 242 Fig. 2a),  $T_i$  is increased dramatically to about 200 eV,  
 243 and  $T_i$  becomes larger than  $T_e$ . All of the above results  
 244 are typical signs of a shock wave. Again, the formation  
 245 of the shock is only possible due to the applied external  
 246 magnetic field. In its absence, as shown in Extended  
 247 Data Fig. 4, we witness no ion temperature increase in  
 248 the same region. Extended Data Fig. 5 shows the elec-  
 249 tron density increase in the shock compared to that of  
 250 the ambient gas.

251 Another important aspect of our experiment is the ob-  
 252 servation of non-thermal protons when the piston inter-  
 253 acts with the magnetized ambient gas. The recorded  
 254 spectra, shown in Fig. 3 (red dots), clearly show the pres-  
 255 ence of non-thermal proton energization when the exter-  
 256 nal magnetic field is applied, i.e. with a spectral slope  
 257 significantly larger than that of the thermal proton spec-  
 258 trum of 200 eV, which is represented by the red dash-dot



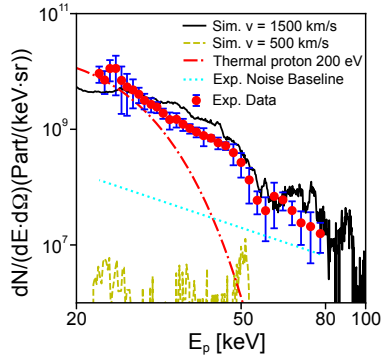
216

217 **Figure 2. Laboratory characterization of electron and**  
 218 **ion temperature increase in the shock.** The measure-  
 219 ments are performed at LULI2000, using collective Thomson  
 220 scattering (TS) on the electron and ion waves in the plasma,  
 221 in a fixed volume 4.3 mm away from the solid target sur-  
 222 face, and with  $B = 20$  T applied (see Methods). Time 0, at  
 223 which a jump is identified, here corresponds to the time at  
 224 which the shock is sweeping through the location of the mea-  
 225 surement. Each data point corresponds to a shot. Panel (a)  
 226 illustrates the local electron temperature inferred from both  
 227 the measurements on the electron and ion waves. Panel (b)  
 228 corresponds to the local ion temperature inferred from the  
 229 measurement on the ion waves. The vertical error bars reflect  
 230 the variations of the parameters when fitting the data with a  
 231 theoretical fit, while still fitting well the data (see examples  
 232 in Extended Data Fig. 4 and 5). The horizontal bar reflects  
 233 the duration (3 ns) of the laser beam used to perform the  
 234 measurement.

259 line. The cutoff energy reaches to about 80 keV, close  
 260 to the Hillas limit<sup>34,35</sup> (an estimate of the maximum en-  
 261 ergy that can be gained in the acceleration region, which  
 262 is around 100 keV with the velocity of 1500 km/s and  
 263 the acceleration length around 3-4 mm in the first 2 ns,  
 264 as shown in Fig. 1f). We stress that without the exter-  
 265 nal B-field or in the absence of ambient gas, no signal  
 266 is recorded in the ion spectrometer (hidden under  
 267 the experimental noise baseline, as indicated by the cyan  
 268 dashed line in Fig. 3).

284 Fig. 1b shows the result of a 3D magneto-  
 285 hydrodynamic (MHD) simulation (performed using the  
 286 FLASH code, see Methods) of the experiment. We ob-  
 287 serve that it reproduces globally the macroscopic expan-  
 288 sion of the piston in the magnetized ambient gas and the  
 289 shock formation (see also Extended Data Fig. 6). How-  
 290 ever, no foot can be observed. What is more, in the MHD  
 291 simulation, the shock velocity is quite steady and does  
 292 not show the strong and fast energy damping experienced  
 293 by the shock from the experiment. Both facts point to  
 294 a non-hydrodynamic origin of the foot and of the energy  
 295 loss experienced by the shock in its initial phase. This  
 296 is why, in the following, we resort to kinetic simulations  
 297 with a Particle-In-Cell (PIC) code (the fully kinetic code  
 298 SMILEI, see Methods). The PIC simulation focuses on  
 299 the dynamics of the shock front (already detached from  
 300 the piston) and of its interaction with the ambient gas,  
 301 using directly the shock parameters measured in the ex-  
 302 periment, and not that of the MHD simulation. As the  
 303 shock changes from super- to sub-critical in its evolution,  
 304 we have performed simulations in two cases (see Fig. 3),



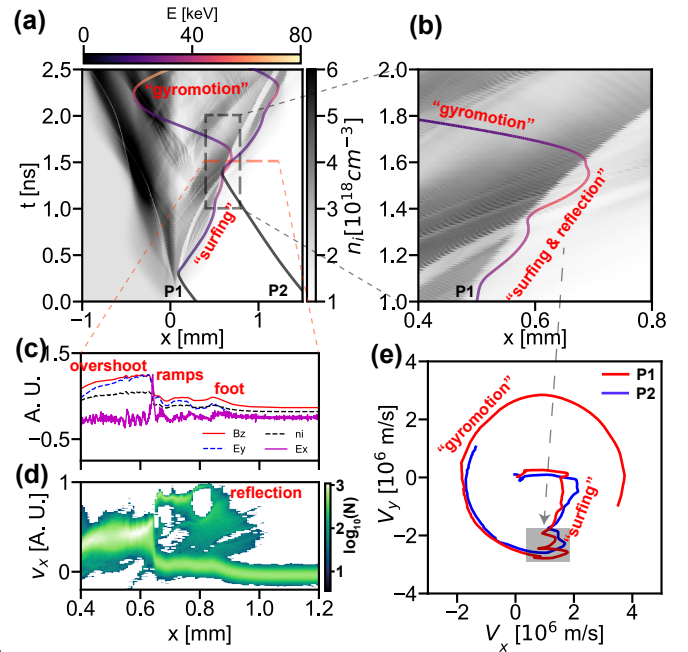


269  
 270 **Figure 3. Evidence for the energization of protons**  
 271 **picked up from the ambient medium.** Proton energy  
 272 spectra of both the experiment (red dots, averaged over five  
 273 shots, as measured at LULI2000) and of two PIC simulations  
 274 (the black solid line for the high-velocity case with  $v = 1500$   
 275 km/s and the yellow dashed line for the low-velocity one with  
 276  $v = 500$  km/s, both are measured at  $t = 2.6$  ns in the simulations)  
 277 of 200 eV. The red dash-dot line is the thermal proton spectrum  
 278 of 200 eV. The blue error bars correspond to one sigma deviation  
 279 from the average (shown by the red dots), the noise level  
 280 on the diagnostic is materialized by the cyan dotted line. Note  
 281 that the absolute scale in proton numbers applies only to the  
 282 experimental spectrum; the simulated spectrum is arbitrarily  
 283 scaled to the experiment one.

305 i.e. with two different velocities representative of the two  
 306 phases, i.e. 1500 and 500 km/s respectively to unveil the  
 307 micro-physics responsible for the observed non-thermal  
 308 proton acceleration.

329 Note that in order to directly compare with the experi-  
 330 mental spectra, the ion specie in our simulation is proton  
 331 with its real mass ( $m_p/m_e = 1836$ ). The PIC simu-  
 332 lation results, for the high-velocity case, are summarized  
 333 in Fig. 4, which identifies clearly the underlying proton  
 334 acceleration mechanism, matching the laboratory proton  
 335 spectrum (see Fig. 3), to be SSA<sup>36</sup>.

336 Fig. 4a illustrates the overall evolution of the early  
 337 stage of the high-velocity shock. Shown is the proton  
 338 density in the reference frame of the contact discontinu-  
 339 ity (CD), where we can clearly see the density pileups  
 340 in the forward direction, indicating the shock formation  
 341 (and periodic reformation<sup>6</sup>). To elucidate the proton ac-  
 342 celeration mechanism, a random sample of protons ( $10^4$   
 343 out of  $10^7$ ) are followed in the simulation. More than  
 344 2% of those end up with energies  $> 40$  keV, which will  
 345 constitute the high-energy end of the spectrum shown in  
 346 Fig. 3. They share similar trajectories and two represen-  
 347 tative ones (P1 and P2) are plotted in Fig. 4a. Following  
 348 these trajectories, we can see that they are first picked up  
 349 by the forward shock at the shock front, and then they  
 350 gain energy while “surfing” along (or confined around)  
 351 the shock front. Besides, while surfing along the shock  
 352 front, P1 gets trapped and reflected repeatedly, with a  
 353 small energy perturbation, as is shown in Fig. 4b, all of



310 **Figure 4. Dynamics of a high-velocity shock and of**  
 311 **the subsequent shock surfing proton energization as**  
 312 **analyzed by PIC simulations.** (a) Trajectories of two pro-  
 313 tons (P1 and P2, energized from the ambient gas to  $> 40$  keV  
 314 at  $t = 2.6$  ns, representing 108 out of 5000 tracked particles  
 315 with the “surfing/reflection/gyromotion” trajectories) in  $x - t$   
 316 diagram, overlaid on the proton density map **in the reference**  
 317 **frame of the contact discontinuity.** (b) Zoom of the black  
 318 dashed rectangle region in (a), showing the “surfing & reflec-  
 319 tion” of P1 along the forward shock. (c) Lineout of density  
 320 and electromagnetic fields (normalized by each of their maxi-  
 321 mum value respectively) at the red dashed line in (a) ( $t = 1.5$   
 322 ns,  $0.4 < x < 1.2$  mm). Note that we also show them separa-  
 323 tely with their units in SI in Extended Data Fig. 10. (d)  
 324 The corresponding proton  $x - v_x$  phase space diagram where  
 325 the colorbar represents the normalized particle number  $N$  in  
 326 logarithm scale. (e) The  $v_x - v_y$  diagram of P1 and P2. The  
 327 grey shaded area corresponds to the “surfing & reflection”  
 328 stage in (b).

354 which is typical of SSA.

355 Typical structures of the super-critical quasi-  
 356 perpendicular collisionless shock<sup>6</sup> can also be seen  
 357 in Fig. 4c where we plot the lineout of density and  
 358 electromagnetic (EM) fields around the shock front  
 359 ( $0.4 < x < 1.2$  mm in the reference frame of the CD),  
 360 when the shock is fully formed ( $t = 1.5$  ns).

361 The longitudinal electric field ( $E_x$ ) is seen to peak right  
 362 at the ramp, providing the electrostatic cross-shock po-  
 363 tential to trap and reflect the protons (with a velocity  
 364 lower than that of the shock). In the corresponding  $x - v_x$   
 365 phase space in Fig. 4d, we can clearly see that, indeed,  
 366 it is at the position of  $E_x$  that protons get reflected (see  
 367 also Extended Data Fig. 7 for more time frames of this  
 368 phase space, as well as for those corresponding to the  
 369 simulation performed at low-velocity). This rules out the

possibility of SDA, where the ion reflection is caused by the downstream compressed B-field<sup>23</sup>, being dominant. At last, as shown in Fig. 4e, the main contribution of the proton energy gain is due to  $v_y$  via the inductive electric field  $E_y = v_x B_z$ , which is again in accordance with the SSA mechanism<sup>37</sup>.

The proton spectrum at  $t = 2.6$  ns produced by the PIC simulated high-velocity shock, and which is shown in Fig. 3 (black solid line), is in remarkable agreement with the experimental observation. As in the experiment, no proton energization is found in the simulations performed without magnetic field or ambient medium. We note also that for the low-velocity shock (with  $v = 500$  km/s), the spectrum (green dashed line) is far below the experimental noise baseline, indicating that the protons are indeed accelerated at the first 2 – 3 ns, when the shock is in the super-critical regime.

Hence, a remarkable outcome of our analysis is that, for the parameters at play in our experiment and at the early stage of the shock formation and development, SSA can be considered as the sole mechanism in picking up thermal ions and accelerating them to hundred keV-scale energies. SSA appears to produce sufficiently energetic protons for further acceleration by DSA, as for example at the Earth’s bow shock, where the threshold energy for DSA to become effective is in the range of  $\sim (50 - 100)$  keV/nucleon<sup>6</sup>. Since we are limited in time in exploring the dynamics of the protons interacting with the super-critical shock, we can only speculate that SDA might appear at a later stage, when the reflected ions acquire enough energy to cross the shock front.

We also note that usually detailed considerations of shock rippling and structuration are evoked in a possible competition between SSA and SDA in the solar wind<sup>12,13</sup>, but that these were not required here in our analysis where we simulate an idealized flat shock front. Although we know that in the experiment, there is likely small structuring developing at the shock front (induced by instabilities<sup>31</sup>, but too small at this early stage to be resolved by our optical probing), these are obviously not required in the modelling to reproduce the experimentally observed energization.

Aside from the solar wind, another interesting case of a shock similar to that investigated here is that of supernova remnants (SNRs) interacting with dense molecular clouds, e.g. the class of Mixed-Morphology SNRs<sup>38</sup>. A large fraction of these SNRs show indications of low energy (MeV) cosmic rays (CRs) interacting with the cloud material and ionising it<sup>39–41</sup>. These mildly relativistic particles are typically explained as CRs accelerated in the past at the SNR shock front that escaped the remnant and reached the cloud<sup>42</sup>. However, our results show that in-situ generation of low energy CRs ( $\sim$  MeV) could be at play, and should also be taken into account<sup>39</sup>. The in-situ acceleration would be most likely generated by the low-velocity, mildly super-critical (see Table 1) SNR shock interacting with the dense cloud; a scenario which is supported by our findings: since our analysis of the

experiment shows that SSA is most likely behind the observed proton energization, and since the plasma parameters at play in the experiment are similar to those of the objects detailed in Extended Data Table 1, we suggest that SSA is similarly effective in these objects.

In conclusion, our experiment provides strong evidence for the generation of super-critical quasi-perpendicular magnetized collisionless shocks in the laboratory. More importantly, non-thermal proton spectra are observed; in our kinetic simulations, they are recognized to be produced by SSA alone. Such efforts for proton acceleration, together with those for electrons<sup>43–45</sup>, will certainly shed new light on the “injection problem” in astrophysically-related collisionless shocks<sup>7</sup>.

The platform we used can be tuned in the future to monitor the transition to DSA, which should be favored by varying the magnetic field orientation, using even higher-strength magnetic field<sup>46</sup> or higher-velocity jets driven by short-pulse lasers as pistons<sup>47</sup>. Another direction will be to test quantitatively the effect of intentionally rippling the shock front by seeding the piston plasma with modulations<sup>48</sup>.

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#### *Author contributions*

J.F. and S.N.C. conceived the project. A.F., S.N.C., K.B., J.B., S.B., S.K., V.L., V.N., S.P., D.C.P., G.R. and J.F. performed the experiments. A.F., E.D.F., S.N.C.,

484 K.B., R.D., S.P. and J.F. analyzed the data. X.R. per-  
 485 formed and analyzed the FLASH simulations, while W.Y.  
 486 and A.F. performed and analyzed the SMILEI simula-  
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 488 E.d.H. and J.F. W.Y., S.N.C., and J.F. wrote the bulk  
 489 of the paper, with major contributions from K.B., M.M.  
 490 and S.O. All authors commented and revised the paper.

491 **Competing interests** The authors declare no com-  
 492 peting interests.

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496 **Data availability** All data needed to evaluate the  
 497 conclusions in the paper are present in the paper. Exper-  
 498 imental data and simulations are respectively archived on  
 499 servers at LULI and LERMA laboratories and are avail-  
 500 able from the corresponding author upon reasonable re-  
 501 quest.

502 **Code availability** The code used to generate Fig. 1b  
 503 is FLASH. The code used to generate part of Fig. 3 and  
 504 Fig. 4 is SMILEI. Both codes are detailed in the Methods  
 505 section.

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