THE ACCELERATION OF THERMAL PROTONS AT PARALLEL COLLISIONLESS SHOCKS: THREE-DIMENSIONAL HYBRID SIMULATIONS

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ABSTRACT

We present three-dimensional hybrid simulations of collisionless shocks that propagate parallel to the background magnetic field to study the acceleration of protons that forms a high-energy tail on the distribution. We focus on the initial acceleration of thermal protons and compare it with results from one-dimensional simulations. We find that for both one- and three-dimensional simulations, particles that end up in the high-energy tail of the distribution later in the simulation gained their initial energy right at the shock. This confirms previous results but is the first to demonstrate this using fully three-dimensional fields. The result is not consistent with the “thermal leakage” model. We also show that the gyrocenters of protons in the three-dimensional simulation can drift away from the magnetic field lines on which they started due to the removal of ignorable coordinates that exist in one- and two-dimensional simulations. Our study clarifies the injection problem for diffusive shock acceleration.

Key words: acceleration of particles -- cosmic rays -- shock waves -- turbulence

Online-only material: color figures

1. INTRODUCTION

Collisionless shocks and the associated acceleration of charged particles are among the most important processes in space physics and astrophysics (Blandford & Eichler 1987). The theory of diffusive shock acceleration (DSA; Krymsky 1977; Axford et al. 1977; Bell 1978; Blandford & Ostriker 1978) describes quantitatively the acceleration process in the vicinity of shock waves. It predicts a power-law energy spectrum downstream of the shock, which is a common characteristic of the energetic charged particles observed in space. However, DSA does not address the physical processes involved with the acceleration of thermal and/or low-energy particles which, presumably, constitute the source of the high-energy particles. This is known as the “injection problem,” which has received a lot of recent attention, but, as yet, there is not a common consensus on its resolution (e.g., Kirk & Dendy 2001).

Collisionless shocks propagating in magnetized plasmas are usually divided into two classes based on the angle, $\theta_{Bn}$, between the incident magnetic field vector and shock normal vector. Quasi-parallel shocks are those for which $0^\circ \leq \theta_{Bn} < 45^\circ$ and quasi-perpendicular shocks are for $45^\circ < \theta_{Bn} < 90^\circ$. For quasi-parallel shocks, there have been several mechanisms proposed in order to solve the injection problem. It is usually thought that for parallel shocks Alfvén waves excited by the streaming of protons can scatter ions in pitch angle. The particles can be accelerated by DSA when their anisotropy is small enough. Ellison (1981) first proposed a Monte Carlo model for DSA that includes the injection process, where the injected particles originate from the shock-heated ions downstream of the shock that then leak back upstream of the shock. Subsequently, the particles are “injected” into the standard DSA process of scattering back and forth across the shock. The model assumes that all the particles are scattered by magnetic fluctuations and ignores the details of the shock structure. It has been used to fit and compare with observations at Earth’s bow shock (Ellison 1985; Ellison et al. 1990). Similar models have also been discussed by other authors (e.g., Malkov 1998; Kang et al. 2012). This is usually referred to as the “thermal leakage” model.

However, a number of authors have found a different scenario for the initial energization at parallel shocks based on self-consistent hybrid simulations (Quest 1988; Scholer & Terasawa 1990; Scholer 1990; Giacalone et al. 1992; Sugiyama & Terasawa 1999; Su et al. 2012). They find that the accelerated ions originate from the shock transition layer rather than the downstream region. Some initial thermal ions are accelerated to high energies as they execute cycloidal motion within the electric and magnetic fields in the shock layer. Although the average incident magnetic field is parallel to the shock normal, as the enhanced upstream magnetic fluctuations steepen and convect through the shock layer, the angle between the incident magnetic field and the shock normal right at the shock front can significantly deviate from the average value and even be close to a quasi-perpendicular shock locally (e.g., Wilson et al. 2013). A particle can gain the first amount of energy by moving against the electric field within the shock layer (Kucharek & Scholer 1991; Giacalone et al. 1992). It has been clearly shown by Kucharek & Scholer (1991) that most of the accelerated particles are reflected by the shock and gain the first increment of energy at the shock layer itself. It is noteworthy that Lyu & Kan (1990) also used hybrid simulations and found that the leakage of protons dominated the accelerated particles. We suggest that the reason they obtained a different result from other authors may be due to the method they used to drive shocks. In their simulations, the upstream and downstream plasmas are initially connected smoothly by assuming a hyperbolic tangent function for the shock parameters with a thickness of several ion inertial lengths. The magnetic fluctuations that are important to reflect ions at the shock front are ignored at the beginning of the simulation. Since the simulation only lasts for $85\Omega^{-1}$, where $\Omega$ is the gyrofrequency of protons in the asymptotic upstream magnetic field, it is difficult to determine if the leakage of protons can dominate the accelerated population of particles after the shock is fully developed. There is observational evidence in support of the idea that particles originate in the shock layer. For example, signatures of ion reflection at the quasi-parallel portion of Earth’s bow shock have been reported (Gosling et al. 1982, 1989). It is worth noting that
Although the initial acceleration in these two processes are quite different, these two models are closely connected and it is difficult to distinguish between them in observations. The Monte Carlo model has been explicitly compared with the results of the hybrid simulations. The comparison generally has a good agreement but some obvious differences (Ellison et al. 1993). The readers are referred to Burgess et al. (2012) for a complete review of these two models.

The injection process at quasi-perpendicular shocks is thought to be more complicated. The required pre-acceleration may be achieved by processes such as shock drift acceleration (e.g., Armstrong et al. 1985; Decker 1988) and shock surfing acceleration (Lee et al. 1996; Zank et al. 1996). In shock drift acceleration, charged particles drift because of the gradient in the magnetic field at the shock front. The direction of the drift is in the same direction as the motional electric field vector $E = -V \times B/c$, and the particles gain energy during this drift motion. In shock surfing acceleration, it is thought that the cross shock potential electric field is a barrier to some particles incident on the shock, leading to their reflection at the shock, and a drift against the motional electric field, leading to the particle acceleration. Recent progress has been made to distinguish the relative importance for these two processes. For instance, it has been found that in order for shock surfing acceleration to be efficient, the thickness of the shock layer has to be very thin—on the scale of an electron inertial length (Lipatov & Zank 1999), which is not consistent with the shocks observed in space and in numerical simulations (Bale et al. 2003; Leroy et al. 1982). Moreover, it has been shown that the shock thickness has to be fairly large compared to electron gyroradii to be consistent with the observation of electron heating at shocks (Lembege et al. 2004). Using one-dimensional hybrid simulations, Wu et al. (2009) showed that the reflection by a cross shock potential electric field is inefficient for suprathermal particles. Yang et al. (2009) and Yang et al. (2012) have used one-dimensional and two-dimensional full particle simulations with test-particle simulations to show that shock drift acceleration dominates the initial acceleration and shock surfing acceleration can sometimes have a considerable contribution.

Giacalone & Jokipii (1999) have demonstrated that large-scale magnetic turbulence which is present in the background plasma can efficiently lower the injection threshold at perpendicular shocks by increasing the transport of charged particles normal to the magnetic field. Recent numerical simulations for the acceleration of charged particles (both ions and electrons) in the existence of large-scale magnetic fluctuations show very efficient acceleration, which indicates that there is no injection problem at perpendicular shocks (Giacalone 2005a, 2005b; Guo & Giacalone 2010, 2012a, 2012b). It is worth noting that observationally there seems no injection problem at quasi-perpendicular shocks. For instance, the Voyager spacecraft clearly shows that energetic particles (at least several MeV) are accelerated at the solar wind termination shock (Decker et al. 2005, 2008). Strong interplanetary shocks observed by the Advanced Composition Explorer and Wind at 1 AU (mostly quasi-perpendicular shocks) can accelerate protons to energies more than 50 keV (Giacalone 2012).

It is important to point out that, in order to accurately model the acceleration of charged particles at shocks, one has to consider fully three-dimensional electromagnetic fields. This is because in a field that has at least one ignorable coordinate, the motions of particles are artificially restricted in the sense that any individual charged particle must remain within one gyro-radius of the magnetic field line on which it began its motion (Jokipii et al. 1993; Giacalone & Jokipii 1994; Jones et al. 1998).

Many previous hybrid simulations were performed using only one or two spatial dimensions (Scholer et al. 1993), and, thus, are subject to this constraint. The effect of cross-field diffusion must be included and requires fully three-dimensional simulations (Giacalone & Ellison 2000). Recent two-dimensional and three-dimensional particle-in-cell simulations have shown signatures of energetic particles at parallel shocks but did not examine the initial acceleration process at the shock front (Niemiec et al. 2012; Caprioli & Spitkovsky 2013).

In this study, we employ a three-dimensional self-consistent hybrid simulation to study the initial particle energization at a parallel shock. We find that all particles accelerated to high energies gain the first amount of energy right at the shock front. In the three-dimensional simulation, the accelerated protons can move off their original field lines. Nevertheless, the initial acceleration process is consistent with that is found in previous one-dimensional and two-dimensional hybrid simulations. This finding clarifies the acceleration of low-energy particles and the injection process for DSA found in other works (e.g., Caprioli & Spitkovsky 2013).

2. NUMERICAL METHOD

We perform three-dimensional hybrid simulations of parallel shocks and compare the results with that of one-dimensional hybrid simulations. Although our simulations resolve the full proton distribution function, we are particularly interested in those particles that are accelerated to high energies. In the hybrid simulations (e.g., Winske & Quest 1988), the ions are treated kinetically and thermal electrons are treated as a massless fluid. This approach is well suited to resolve ion-scale plasma physics, which is crucial to describe supercritical collisionless shocks and particle acceleration from thermal to suprathermal energies. We have improved the efficiency of our one-dimensional, two-dimensional, and three-dimensional hybrid simulation models (Section 3.3.1 in Guo 2012). The new codes have been implemented and tested on NASA’s Pleiades supercomputer using a few thousand CPU cores. For the three-dimensional simulations, we consider a three-dimensional Cartesian grid (x, y, z). All the physical vectors such as the positions and velocities of protons, and electric and magnetic fields $E$ and $B$ have components in three directions and also spatially depend on x, y, and z. For the one-dimensional simulations, the physical vectors have components in three directions but only depend on x. A shock is produced by using the so-called piston method, in which the plasma is injected continuously from one end of the simulation box (x = 0, in our case), and reflected elastically at the other end (x = Lx). The right boundary is assumed to be a perfectly conducting barrier. The pileup of density and magnetic field creates a shock propagating in the $-x$ direction. In the three-dimensional simulation, the boundary conditions of the electromagnetic fields in the y- and z-directions are periodic, and the particles that move out of one end of the simulation domain in y- or z-directions will re-enter the domain from the other end.

We examine two different simulation cases (one-dimensional and three-dimensional) with similar parameters. In both cases, the Mach number of the flow in the simulation frame is $M_{A0} = V_{A0}/V_A = 4.0$, where $V_{A0}$ is the upstream Alfvén speed. The electron and ion plasma betas are $\beta_e = 1.0$ and $\beta_i = 0.5$, respectively. The grid size is $\Delta x \times \Delta y \times \Delta z = 0.5c/\omega_{pi} \times 0.5c/\omega_{pi} \times 0.5c/\omega_{pi}$ for the three-dimensional case
and \( \Delta x = 0.5c/\omega_{pi} \) for the one-dimensional simulation case, where \( c/\omega_{pi} \) is the ion inertial length, and \( c \) and \( \omega_{pi} \) are the light speed and proton plasma frequency, respectively. The time step is taken to be \( \Omega_{ci}\Delta t = 0.01 \), where \( \Omega_{ci} \) is the proton gyrofrequency. The ratio between light speed and upstream Alfvén speed is \( c/v_{A0} = 6000.0 \), and the anomalous resistivity is \( \eta = 1 \times 10^{-8}4\pi\omega_{pi}^{-1} \). The initial spatially uniform thermal ion distribution is represented using 25 particles per cell in the three-dimensional case and 200 particles per cell in the one-dimensional case. We have repeated the simulations with different number of particles per cell and found that it does not change the results. Initially the average magnetic field is assumed to be \( B_0 = B_0\hat{x} \), i.e., the average shock-normal angle is zero. The spatial size in the \( x \)-direction is taken to be 300c/\( \omega_{pi} \) for both of the cases. For the three-dimensional case, the lengths of the simulation box in the \( y \) - and \( z \) -directions are taken to be \( L_y = L_z = 40c/\omega_{pi} \). Pre-existing magnetic fluctuations are not included (Giacalone et al. 1992).

3. SIMULATION RESULTS

Figure 1 shows results from the three-dimensional simulation. Shown are representations of various quantities in the \( x-y \) plane at \( z = 20 c/\omega_{pi} \) at \( \Omega_{ci}t = 120.0 \). The figure shows the color-coded contours of (a) the magnitude of the magnetic field \( B/B_0 \), (b) the \( x \)-component of the bulk proton velocity \( V_x/V_{A0} \), (c) the density of the plasma flow \( n/n_0 \), and (d) the density of accelerated particles with energy \( 3E_1 < E < 5E_1 \), where \( E_1 \) represents the upstream proton ram energy \( m_pU_1^2/2 \) in the shock frame and \( U_1 \) is taken to be 5.3\( V_{A0} \).

Figure 2. One-dimensional \( x \)-profiles from the three-dimensional simulation at \( y = 20c/\omega_{pi} \) and \( z = 20c/\omega_{pi} \) (solid black lines) and the one-dimensional simulation (dashed red lines): (a) plasma number density \( n/n_0 \), (b) the magnitude of the magnetic field \( B/B_0 \), and (c) the \( x \)-component of the bulk proton velocity \( V_x/V_{A0} \).

Figure 3 shows results from the three-dimensional simulation at \( \Omega_{ci}t = 120.0 \) along the same line with that in Figure 2, but for the magnetic field components \( B_x/B_0 \), \( B_y/B_0 \), and \( B_z/B_0 \), respectively. The dashed red lines represent the results from the one-dimensional simulation at \( \Omega_{ci}t = 110.0 \). Note that in one-dimensional simulations, \( B_z \) is always taken to be 0 (not...
For the one-dimensional simulation, the location of the shock in the $x$-direction is about $x = 132c/\omega_{pi}$ and the upstream inflow speed in the shock frame is about $U_1 = 5.5V_{A0}$, slightly larger than that in the three-dimensional simulation. For the three-dimensional case, the magnetic field fluctuations are mostly transverse to the initial magnetic field in the $x$-direction. The fluctuating components $\delta B_x$ and $\delta B_z$ contain about 90% of the total energy of the magnetic fluctuations. The fluctuations are circularly right-handed polarized, and are convected toward the shock, indicating that they are excited by reflected ions that flow upstream. Close to the shock, the fluctuations are compressed and amplified. The downstream magnetic field consists of large-amplitude fluctuations. The results are consistent with previous analytical theories and one-dimensional numerical simulations (e.g., Quest 1988). The results from three-dimensional simulations are qualitatively consistent with those from the one-dimensional simulation.

Figure 4 gives a three-dimensional representation of the magnitude of magnetic field $B/B_0$ close to the shock region at $\Omega_{ci}t = 120.0$. The two-dimensional slice at $x = 146c/\omega_{pi}$ plane clearly shows the transition of the magnetic field. The shock front is highly turbulent due to its interaction with upstream fluctuations, which produces various enhancements of magnetic field at different regions. This is similar to recent results of large-scale multi-dimensional hybrid simulations (Lin & Wang 2005; Omidi et al. 2013; Caprioli & Spitkovsky 2013). Due to the limited box size and simulation time, the size of structures in the shock surface can only grow to $\sim 10-20c/\omega_{pi}$, which is smaller than that in recent large-scale hybrid simulations (Omidi et al. 2013; Caprioli & Spitkovsky 2013). The three-dimensional features at parallel shock regions will be further investigated in the future.

Now we discuss the acceleration of protons at the shock front. Jokipii et al. (1993), Giacalone & Jokipii (1994), and Jones et al. (1998) have demonstrated that in simulation models with at least one ignorable coordinate, the guiding center of an individual charged particle is confined to within one gyroradius of the magnetic field line on which it began its motion. In order to overcome this artificial constraint and to accurately model the acceleration process, it is important to consider the motions of charged particles in three-dimensional electric and magnetic fields. Since we perform three-dimensional hybrid simulations in this study, the restriction on the motions of charged particles is removed.

Figure 5 shows the trajectory of a representative particle in the one-dimensional simulation. The physical quantities for each panel are (a) the energy versus the location in the $x$-direction away from the shock front in the shock frame $x_{sh}$ (the location of the shock front is assumed to be $x_{sh} = 0$), (b) the energy versus the time in the simulation, (c) the location in the $z$-direction $z = \int v_zdt + z_0$ versus the location in the $y$-direction $y = \int v_ydt + y_0$, where $y_0$ and $z_0$ are assumed to be zero, respectively. The marker “1” notes the starting point and “2” notes the end point of the trajectory. One can clearly see that the initial acceleration occurs right at the shock front $x_{sh} = 0$. The acceleration mechanism is due to the reflection at the shock, and the particle gains energy in the electric field $E = -V \times B/c$, since locally the angle between magnetic field vector and shock normal vector can be quite large. As shown in this figure, the particle “rides” along the shock front and is accelerated for about 15 gyroperiods. The resulting energy gain is about 10 times the plasma ram energy $E_1$. This process has been discussed by previous authors (Quest 1988; Scholer & Terasawa 1990; Scholer 1990; Kucharek & Scholer 1991; Giacalone et al. 1992) and our results are consistent with previous work. Since we use the one-dimensional hybrid simulation, the motion of the particle is restricted on its original field line and its guiding center to within one gyroradius of the initial field line.

In Figure 6 we show the trajectory of an accelerated particle in the three-dimensional simulation. The plotted physical quantities are similar to Figure 5. Since the electric and...
The trajectory of a representative particle accelerated at the shock layer from the one-dimensional simulation. The physical quantities for each panel are (a) the energy vs. the distance away from the shock layer, (b) the energy vs. the time in the simulation, (c) the simulation time vs. the distance away from the shock, and (d) the location along the z-direction $z = \int v_z dt + z_0$ vs. the location along the y-direction $y = \int v_y dt + y_0$, assuming the initial location is at $y_0 = 0$ and $z_0 = 0$.

Figure 5.

The trajectory of a representative particle accelerated at the shock layer from the three-dimensional simulation. The plotted physical quantities are similar to Figure 5.

Figure 6.

The energy of the particle is represented by its color. It clearly shows the reflection of the particle at shock front, and the particle gains energy during the gyromotion. Eventually the particle can gain energy up to $40E_1$ and drift several tens of ion inertial lengths away from its original location along the z-direction.

However, even in the three-dimensional simulation we find that the acceleration process is quite similar to what is found in the one-dimensional simulation. The particles still gain their first amount of energy at the shock front. We have examined several hundred accelerated particles in the three-dimensional simulation and found that they all get the initial acceleration right at the shock layer.

Figure 7.

Three-dimensional trajectory of an accelerated particle in the three-dimensional simulation during $\Omega_c t = 22.0–92.0$. The energy of the particle is represented by its color. The energy of the particle is represented by its color. It clearly shows the reflection of the particle at shock front, and the particle gains energy during the gyromotion. Eventually the particle can gain energy up to $40E_1$ and drift several tens of ion inertial lengths away from its original location along the z-direction.

Figure 8.

Locations of 50 accelerated particles in the x-direction as a function of simulation time. The particles are tracked until they gain energies several times the plasma ram energy. It shows that all the accelerated particles gain initial energies at the shock layer.

magnetic fields are fully three-dimensional, this particle (and all others) is not restricted to its original field line as in the one-dimensional simulation. This can be seen from Figure 6(d), in which the guiding center of the charged particle drifts in the y–z plane away from its original field line during the acceleration. We have examined the trajectory of this particle until the end of the simulation and found that its guiding center does not move back to within one gyroradius of the position of the field line that the particle started its gyromotion. The original field line is not likely far away (in the y–z plane) from where it was originally. In order for this to happen, there would have to be significant flows in the y- and z-direction upstream of the shock. Figure 7 shows the three-dimensional trajectory of an accelerated particle in the three-dimensional simulation during $\Omega_c t = 22.0–92.0$. The energy of the particle is represented by its color. It clearly shows the reflection of the particle at shock front, and the particle gains energy during the gyromotion. Eventually the particle can gain energy up to $40E_1$ and drift several tens of ion inertial lengths away from its original location along the z-direction.
are initially evenly distributed along line at $\Omega$ and track their motions during the simulation. The test particles (one-dimensional simulation) at the beginning of the simulation are restricted. It can be seen that in the one-dimensional simulation, the distribution of the particles has no obvious structure, indicating that they move off their original field line. Giacalone & Jokipii (1994) have shown that in one-dimensional and two-dimensional numerical simulations, the motions of charged particles are restricted. Here we show that this restriction is indeed removed in the three-dimensional hybrid simulation. We also observe that some test particles can move a large distance ($> 40c/\omega_{pi}$) transverse to the magnetic field in the three-dimensional simulation.

In Figure 8 we plot the probability distribution functions (PDFs) for the transverse displacement from the initial location $\sqrt{\Delta y^2 + \Delta z^2}$ from the two cases shown in Figure 9. The solid black line represents the results from the three-dimensional simulation and the dashed red line represents the results from the one-dimensional simulation. The PDFs have been normalized using the counted number of particles. It can be seen that a significant fraction of the particles can move a large distance ($> 40c/\omega_{pi}$) in the transverse direction because the particles can move off their original field line. In the one-dimensional simulation, the transverse motion is restricted within about $20c/\omega_{pi}$. In our case, the field line meandering due to the large-amplitude magnetic fluctuation can cause some particles to move transverse to the $x$-direction. However, the results for the one-dimensional simulation (Figures 9 and 10) are consistent with Giacalone (1994), who demonstrated the particles have a restricted cross-field motion in one- and two-dimensional fields by simulating a quasi-perpendicular shock with $\theta_{Bn} = 45^\circ$.

In Figure 11 we show a comparison of the downstream energy spectra at $\Omega, t = 120.0$ between the one- and three-dimensional simulations. The solid black line shows the spectrum for the three-dimensional simulation and the dashed blue line represents the spectrum for the one-dimensional simulation. A Maxwellian distribution determined from shock jump relation is also shown using dotted red line. In both cases, a fraction of thermal protons are accelerated to more than several times the plasma ram energy, $E_1$. The acceleration at the shock layer can have a significant contribution to nonthermal tails in the energy spectra. Since in the one-dimensional simulation we

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{Displacements of particles from their original positions in the $z$-direction vs. the location of particles in the $x$-direction. The upper panel shows the results from the one-dimensional simulation. The bottom panel shows the results from the test particles that are initially on the same field line $y = 20c/\omega_{pi}$ and $z = 20c/\omega_{pi}$ in the three-dimensional simulation.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Probability distribution function (PDFs) for the transverse displacements of the particles in the downstream region. The solid black line is for the test particles originally along $y = 20c/\omega_{pi}$ and $z = 20c/\omega_{pi}$ in the three-dimensional simulation and the dashed red line is for the one-dimensional simulation. The PDFs have been normalized using the counted number of particles. (A color version of this figure is available in the online journal.)}
\end{figure}
have a limited number of particles, the spectrum only extends to about 200 \(m_pV_{A0}^2/2\). For the three-dimensional simulation, the particles can be energized up to 600 \(m_pV_{A0}^2/2\). In both cases, the density of the accelerated particles with energy larger than 20 \(m_pV_{A0}^2\) is about 5% of the downstream plasma density, indicating an efficient injection of energetic particles.

**4. DISCUSSION AND CONCLUSIONS**

We performed three-dimensional hybrid (kinetic ions and fluid electrons) simulations to investigate the initial acceleration of thermal protons at parallel shocks. We examined the trajectories of many individual particles and the spatial distribution of protons that comprise the high-energy tail resulting from the acceleration of particles at the shock. We find that the charged particles gain energy at the shock layer similar to the one-dimensional simulation. The particle can ride on the shock front and gain a large amount of energy. The results confirm previous hybrid simulations that the initial energization is due to the ion reflection and acceleration at the shock layer, the results were obtained only for one-dimensional simulations and occasionally two-dimensional simulations. As pointed out by Jokipii et al. (1993), Giacalone & Jokipii (1994), and Jones et al. (1998), in a magnetic field that has at least one ignorable coordinate, the motions of charged particles are restricted on their original field lines of force. In this sense, the previous simulations are not conclusive. In this work, we have demonstrated that the reflection at the shock layer is the mechanism for accelerated particles gaining their initial energy in a self-consistent, three-dimensional field. However, our results are not consistent with the “thermal leakage” model, which assumes that the thermal particles gain the first amount of energy by a thermalization process in the downstream region.

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