

NUMERICAL SIMULATIONS OF COLLISIONLESS SHOCK FORMATION IN MERGING PLASMA JET EXPERIMENTS*

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Abstract

In ongoing experiments at the Plasma Liner Experiment (PLX) facility at Los Alamos National Laboratory, two high Mach number plasma jets, composed of gases such as H and Ar, will be collided. We describe numerical simulations using particle-in-cell (PIC) and hybrid-PIC methods using the code LSP. Using expected experimental plasma conditions ($n \sim 10^{14}$ - 10^{16} cm⁻³) large scale transport simulations demonstrate that the jets are essentially collisionless at the merge point. In smaller-scale 1D and 2D simulations we show that collisionless shocks are generated by the merging jets when immersed in applied magnetic fields ($B \sim 0.1$ - 1 T). Unmagnetized collisionless shocks are not found in simulations at the expected jet velocities (10-100 km/s). Considerably higher velocities are required to see this effect. The orientation of the magnetic fields and the axial and transverse gradients of the jets are shown to have strong effect on the nature of the interaction.

I. INTRODUCTION

Collisionless shocks play an important role in energy transport and evolution of charged-particle distribution functions in space and astrophysical environments. Although collisionless shocks in plasmas were first predicted in the 1950s [1] and discovered in the 1960s [2] many questions relating to the microscopic physics of collisionless shock formation, evolution, and shock acceleration of particles to very high energies remain unanswered. Laboratory studies of collisionless shocks have been conducted since the 1960s but a recent renaissance of laboratory collisionless shock experiments stems from the fact that modern laboratory plasmas can satisfy key physics criteria for the shocks to have “cosmic relevance” [4]. Recently initiated experiments [5] at Los Alamos National Laboratory (LANL) aim to form and

study astrophysically relevant collisionless shocks via the head-on merging of two supersonic plasma jets. Compared to many other modern collisionless shock experiments the LANL experiment has larger shock spatial size (up to 30-cm wide and a few-cm thick) and longer shock time duration (order 10 μ s) but somewhat lower sonic and Alfvén Mach numbers. The LANL experiment plans to have the capability to apply magnetic fields of a few kG (via coils) that can be oriented either parallel or perpendicular to the direction of shock propagation. This paper reports results from particle-in-cell (PIC) and hybrid-PIC numerical simulations, using the LSP code [6]-[7] that informed the design of the LANL experiment and showed that collisionless shocks should appear with the expected plasma jet parameters.

After a brief description of the LANL collisionless shock experiment, the remainder of the paper describes single-jet propagation and one- (1D) and two-dimensional (2D) PIC head-on merging jet simulations. Our 1D magnetized simulations, in which the jets are immersed in an applied magnetic field, are similar to those of Shimada and Hoshino [8] who performed 1D PIC simulations of magnetized shock formation using a reduced ion-to-electron mass ratio. We use the actual hydrogen mass ratio and the actual hydrogen plasma parameters expected in the LANL experiments. We have also performed 2D Cartesian merging simulations of magnetized jets which allows us to consider the effects of the orientation of the magnetic field and plasma density gradients with respect to the jet propagation direction. These simulations demonstrate shock formation caused by the merging of magnetized jets with Mach numbers as low as ~ 1.5 .

In unmagnetized plasmas, collisionless shocks may also be formed by the Weibel instability [9]. Simulations of this mechanism were described by Kato and Takabe [10], whose simulations were also performed at a reduced mass ratio and were restricted to relatively high velocities ($> 0.1c$). When using the hydrogen mass ratio and a lower

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velocity (~ 100 km/s as expected in the experiment), we find no shock formation on relevant timescales (a few μ s).

II. DESCRIPTION OF EXPERIMENT AND SIMULATION MODEL

The simulations described in this paper are based on the LANL collisionless shock experiment [5], which uses counter-propagating hydrogen plasma jets formed and launched by plasma railguns [11] mounted on opposite sides of a 2.74 m diameter spherical vacuum chamber (Fig. 1).

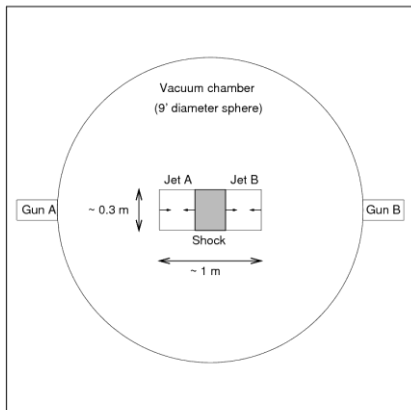


Figure 1. Schematic view of experiment simulated in this paper.

The approach used in this numerical study is two-fold. We initially perform a large-scale simulation of a single jet propagating from the end of the plasma gun to the center of the vacuum chamber. The hydrogen jets emerge from the plasma gun with densities on the order of 10^{14} - 10^{16} cm^{-3} and temperatures of a few eV. The jets emerging from the guns will be few centimeters in size with masses of a few μg , and will have a drift velocity ~ 100 km/s. But both must propagate on the order of 1 m before merging can begin, during which time the density, temperature, and equation-of-state (EOS) of the jet can change. The single-jet propagation simulation models the time evolution of the initial jet as it propagates through the chamber. This 2D- rz simulation must be run for several μ s. This requires using a fairly large timestep, for which $\omega_{pe} \Delta t \gg 1$, at an initial plasma density $\sim 10^{16}$ cm^{-3} . Such simulations must be done with a hybrid-PIC approach in which electron plasma oscillations do not need to be resolved.

However, a fully kinetic approach is required to model the formation of shocks due to micro-instabilities induced by jet merging. As will be seen below, the hydrogen jets ejected from the plasma guns drop considerably in density as they propagate to the center of the chamber where the merging takes place. This density reduction during propagation allows us to perform fully kinetic explicit PIC merging simulations in 1D and 2D Cartesian coordinates in which electron timescales are resolved.

These simulations, which are initialized with plasma parameters obtained from the propagation simulation, are intended to model only the merging process which occurs much later than the ejection of the jets from the guns.

All of these simulations are performed using the hybrid-PIC code LSP. In addition to the traditional PIC formalism, LSP also contains algorithms for dense plasma simulation and includes physics modules for collisions (among charged and neutral species), EOS modeling, and radiation transport. This flexibility available in the code makes it useful for the two-fold simulation approach described above.

III. SINGLE JET PROPAGATION

Hybrid-PIC LSP simulations were performed of a single hydrogen plasma jet propagating from the railgun nozzle to the center of the chamber in order to connect the plasma jet parameters at the railgun exit with those in the region of head-on jet merging. The 2D- rz simulation space is large enough to allow for propagation of the initial jet from the exit of the gun to the center of the vacuum chamber. The simulation uses a quasi-neutral hybrid-PIC algorithm [12] which has fewer constraints on the timestep. The ion macroparticles are kinetic. But there are no electron macroparticles, as the ions carry fluid information for the inertia-less electrons. Coulomb collisions are included for electrons and ions.

The plasma EOS (plasma internal energy, charge state, etc.) is provided by the PROPACEOS code [13], as are photon emission opacities, which allows modeling of radiation losses in optically-thin plasmas. The cell size is $\Delta r = \Delta z = 0.5$ cm, and there are ~ 1000 ion macroparticles per cell.

The initial profile of the ion density, n_i , can be seen in the upper left plot in Fig. 2. At $t = 0$ the single jet is assumed to have a peak density of 10^{16} cm^{-3} , electron and ion temperatures $T_e(0) = T_i(0) = 5$ eV, and jet velocity $v_j = 150$ km/s.

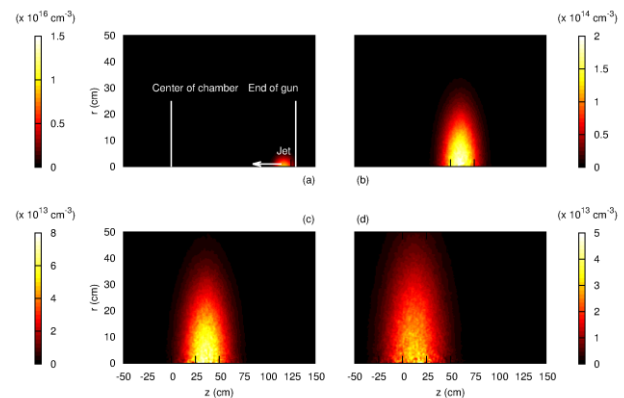


Figure 2. Snapshots of ion density in a 2D- rz hybrid-PIC simulation of hydrogen jet propagation

The time evolution of the jet propagation can be seen in Fig.2 which shows n_i contours at $t =$ (a) 0, (b) 3.8, (c) 5.4, and (d) 7 μ s. The approximate plasma parameters of the jet at the railgun exit and center of the chamber ($z = 0$ cm) are given in Table 1. So this simulation determines the approximate parameter regime of the individual jets after they have propagated to the center of the chamber and begun to merge: $n_i \sim 10^{13}$ cm $^{-3}$, $v_j \sim 150$ km/s, $T_e \sim T_i \sim 1$ eV, $n_e/n_i \sim 1$, and jet length, $L_j \sim 50$ cm. The density gradient scale length, $L_d \sim L_j$.

Table 1. Initial and approximate parameters at the center of the chamber ($z = 0$; $t \simeq 8400$ ns) in 2D- rz jet propagation simulation.

Quantity	Railgun Exit	Chamber Center
n_e (cm $^{-3}$)	10^{16}	9×10^{12}
n_i (cm $^{-3}$)	10^{16}	2×10^{13}
T_e (eV)	5	1.25
T_i (eV)	5	0.4
v_j (km/s)	150	150

Based on the results of this simulation, we have chosen a set of simplified plasma parameters to be used for the fully kinetic simulations discussed in the following sections. These values are given in Table 2.

Table 2. Initial jet parameters used in 1D and 2D fully kinetic propagation and merging simulations.

Quantity	Value
$n_i = n_e$ (cm $^{-3}$)	10^{13}
$T_i = T_e$ (eV)	1
v_j (km/s)	150
L_j (cm)	~ 50
L_d (cm)	varies: $\sim [0, L_j]$
B (G)	varies: $\sim [0, 1500]$
v_{ii}^{-1} (s)	$\sim 10^{-4}$
v_{ie}^{-1} (s)	$\sim 10^{-5}$
L_j/v_j (s)	$\sim 10^{-6}$

Using these parameters we can estimate the Coulomb collision frequency for the jets. To observe collisionless merging of the jets, it is necessary that the inter-jet ion collision time be much larger than the jet interaction time. Using the parameters above, we find ion-ion collision time $v_{ii}^{-1} \sim 10^{-4}$ s and ion-electron collision time $v_{ie}^{-1} \sim 10^{-5}$ s, while the jet interaction time $L_j/v_j \sim 10^{-6}$ s. So this simulation result demonstrates that these counter-propagating jets will indeed be in the collisionless regime when the jets merge at the center of the chamber.

IV. WEIBEL MEDIATED UNMAGNETIZED SHOCKS

One possible collisionless shock mechanism is a Weibel-mediated unmagnetized shock driven by a 2D electromagnetic kinetic instability when the two jets

merge. In 2D PIC simulations, Kato et al. [10] found unmagnetized Weibel-mediated shocks formed by merging jets with “non-relativistic” velocities $v_j/c = 0.1-0.45$. Using LSP in similar simulations, we are able to reproduce the results of Kato for collisionless merging jets with velocities in this velocity range. But $0.1c$ is still 200 times faster than the 150 km/s jet velocities expected in the LANL experiments. When scaling the Weibel simulations down to the experimental parameter regime (Table 2), we find no evidence of shock formation or any strong jet interaction over μ s time scales, suggesting that the LANL experiment will not give rise to unmagnetized collisionless shocks.

V. 1D MAGNETIZED SHOCKS IN MERGING JETS

The 1D Cartesian fully-kinetic merging simulations are intended to model the merging of jets near the chamber center. Since we have seen that the plasma density near the chamber center is much lower than at the gun exit (see Table 1), this allows us to do explicit kinetic PIC simulations. We can also afford better spatial and temporal resolution in 1D Cartesian coordinates: $\Delta x = 2c \Delta t = 0.03$ cm. Both electrons and ions are modeled kinetically. Coulomb collisions are included for the electron species, as are ion collisions, which are found to have a negligible effect in this parameter regime. The 1D simulations described below are all run with several thousand macroparticles per cell. We assume fully-stripped hydrogen ions for simplicity. We also assume an ideal gas EOS for the plasma jets and neglect radiation losses.

The results of a 1D simulation of jet merging in an applied field of $B_z = 1000$ G are shown in Fig. 3, which shows ion density (top) and B_z profiles (middle), and ion macroparticle x - v_x phase-space data (bottom) as a function of x at (left) $t = 0$ and (right) $t = 260$ ns. The full plasma initial conditions are given in Table 2. There is clear propagation of a shock wave. At the later time there is a finite width shock transition region, with clear pre- and post-shocked regions with roughly constant density and field values for each region. The persistence of the density null at $x = 0$ can be explained as follows. Each jet travels in a motional field $E_y \sim v_x B_z$, which has opposite signs for the two jets. At the merge point, $x = 0$, the motional fields cancel and the plasma can no longer propagate in the magnetic field. Alternately, the enhanced magnetic field in the shocked region is supported by plasma currents at the shock edge. The $J \times B$ force decelerates the plasma from a drift velocity of v_j in the pre-shocked region to zero in the post-shocked region. This can be seen in the phase-space plots. Since the plasma is stationary behind the shock, the density profile remains relatively constant in time. At early times, as the jets begin to merge, the electric field E_x , which establishes the current flow, can be seen in the simulation results. This field also causes the

acceleration of a small population of ions near $x = 0$ cm, which can be seen in Fig. 3.

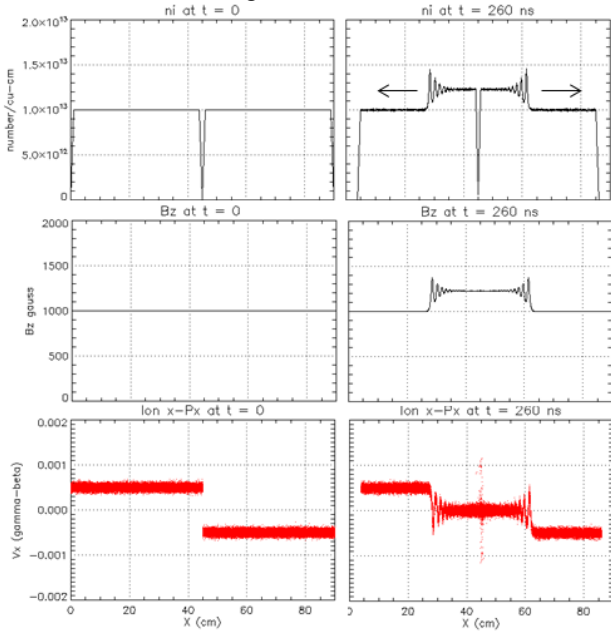


Figure 3. Simulation (1D) results for two counter-propagating jets with an applied perpendicular field (in $+z$ direction) of 1 kG.

We have demonstrated the development of a propagating shock wave in simulations with a perpendicular magnetic field. We find *no* interaction between the jets if a *parallel* magnetic field is applied. There is also *no* interaction for small values of perpendicular magnetic field, i.e., when $v_A \ll v_j$, where v_A is the Alfvén velocity calculated at the applied field strength.

We have performed a series of simulations with varying values of applied field. For these simple 1D simulations, it is possible to compare our results to the theoretical Rankine-Hugoniot conditions for collisionless shocks in perpendicular fields given by Tidman and Krall [14]. We find good agreement between our simulations and the theory for the ratios of pre- and post-shocked values for density, magnetic field, and velocity. This gives us confidence that we can quantitatively describe shock phenomena using PIC methods. Moreover, the PIC simulations also show kinetic effects such as the ion acceleration at $x = 0$ seen in Fig. 3. These effects are neglected in the theory which assumes Maxwellian distributions for both electrons and ions.

The previous 1D shock simulations were performed with very steep density gradients (on the order of one or two cell widths), and a uniform density in the bulk. These profiles were chosen because they exhibited very clear shock structure and allowed direct comparison with the 1D theory. We now add more realistic density gradients. In the experiment we expect density profiles such as those seen at later times in Fig. 2, with $L_d \sim L_j$. The applied field is again $B_z = 1000$ G, and the maximum initial density

remains 10^{13} cm $^{-3}$. The initial density profile can be seen at the top left of Fig. 4. The time evolution of the density, particle phase-space, and magnetic field can be inferred from the figure as well. We note, at $t = 260$ ns, that there is still a clear shock wave structure visible when finite density gradients are included. Due to the presence of initial density gradients, there are no constant post-shock values of density and field, but the sharp shock transition region is evident.

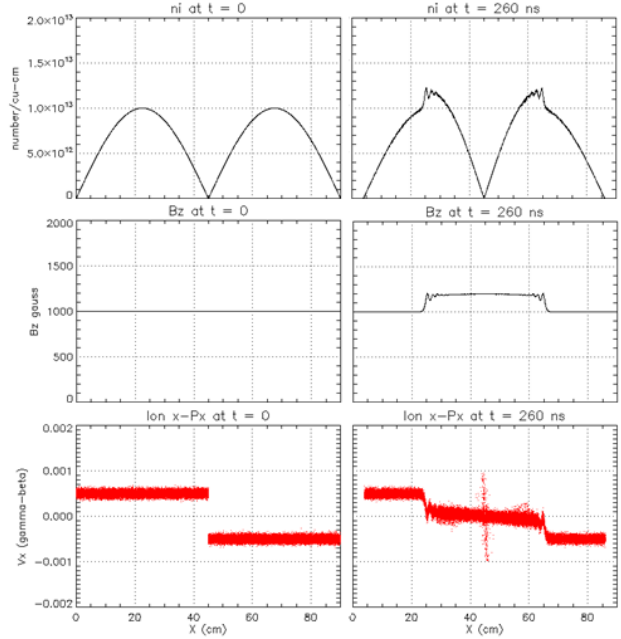


Figure 4. Simulation (1D) results for two counter-propagating jets with finite density gradients in an applied perpendicular magnetic field (1 kG in the $+z$ direction).

All the 1D shock simulations discussed above were initialized with two counter-propagating jets adjacent to each other (see the top left of Fig. 3). We now wish to consider the effect of an initial jet separation. We repeat the simulation in Fig. 3 with constant bulk density and sharp density gradients but with a field value $B_z = 350$ G. We also introduce a large initial jet separation $L_g(0) \sim L_j$. The initial geometry is shown in Fig. 5, as well as the ion density, ion particle phase-space, and magnetic field at $t = 500$ ns. The interaction seen in this figure is not a shock wave. At these early times there is no clear post-shocked region: the density and field never reach constant steady-state values (despite the uniform initial density). Moreover, the disturbance propagates into the jet at a speed v_A (in the jet rest frame). It is only at later times, when there is a significant population of ions with $v_x \sim 0$, that a shock wave begins to form.

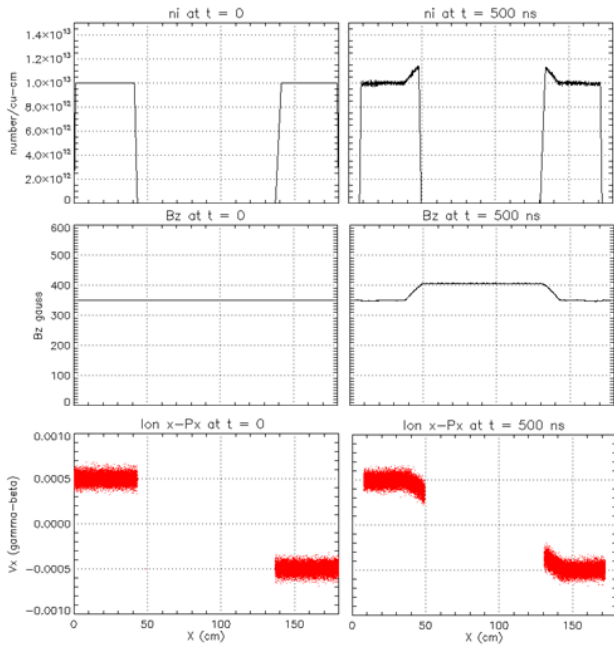


Figure 5. Simulation (1D) results for two counter-propagating jets with a 350 G perpendicular field in the $+z$ direction and an initial jet separation of ~ 90 cm.

A simple model can be used to explain the early-time behavior (pre-shock) of the 1D counter-propagating jet simulations with an initial jet separation. In all 1D simulations with $L_g(0) > 0$ (before the onset of shock waves), we observe flux conservation, i.e., $L_g(t) \times B_m(t)$ is constant, where B_m is the field value at the midpoint between the jets. A uniform acceleration of the gap width is also found. To derive an estimate for the gap acceleration, we consider a simplified model of the 1D simulations. We neglect displacement current, assume linear ramps on B_z , and a piecewise constant current J_y . By imposing flux conservation and assuming a $J \times B$ force on the plasma in the transition region, we obtain an acceleration of $a = 4 v_A v_j / L_g(0)$. LSP simulations are found to be in relatively good agreement with the simple scaling derived above. If we define the minimum jet separation as L_{min} , our simple theory predicts that $L_{min} / L_g(0) = 1 - v_j / 2v_A$. This implies that the jets will not overlap unless $v_j > 2 v_A$. But, in general, the shock waves start before L_g can reach 0.

VI. 2D MAGNETIZED SHOCKS IN MERGING JETS

The last group of simulations considered in this paper are in 2D Cartesian coordinates. We simulate the 2D jets in the xy plane, with the jets propagating in the x direction. The total y extent is many ion skin depths wide. To maintain reasonable runtimes, 2D simulations performed at realistic length require coarser spatial resolution ($\Delta x = \Delta y = 2 c \Delta t = 0.24$ cm) and a smaller

number of particles per cell (tens rather than hundreds) than were possible in 1D.

In these simulations we find some slow numerical heating of the electrons at later times due to the coarse spatial resolution of the grid ($\Delta x \sim c/\omega_{pe}$). However, if the simulation duration does not exceed $\sim 1 \mu s$, the energy conservation remains good to within a few percent. High fidelity simulations over longer time scales will require better spatial resolution and larger particle numbers. This will require the use of more processors than were available.

Results from a 2D simulation with a 350-G magnetic field in the virtual direction ($+z$) are shown in Fig. 6. The density and field contours are shown at various times. We notice, however, that there is a conspicuous difference between this simulation and the 1D (Fig. 3) analog. Namely, the density at the center-of-mass of the two jets, along the line at $x = 0$, remains large ($> 10^{13} \text{ cm}^{-3}$) throughout the simulation, indicating at least some jet interpenetration at this point. In the 1D analog, the density remained close to zero at the jet center of mass.

In order to explain this qualitatively different behavior, we consider first the results for a 2D simulation in which the 350-G field is rotated from the virtual $+z$ to the $+y$ direction, which lies in the simulation plane. These results are shown in Fig. 7. For this magnetic field orientation, the results are qualitatively similar to the 1D case, as n_i remains zero along $x = 0$. When the magnetic field is in the y direction (Fig. 7), the currents which drive the enhanced magnetic field can flow in the virtual z direction and remain localized near $x = 0$ cm. This allows for large $J \times B$ forces to reflect the incoming jets. When the magnetic field is in the virtual z -direction (Fig. 7) the magnetic field is supported by finite circular current paths around the perimeter of the bulk of the jet. The density gradient in y acts to minimize the x component of the $J \times B$ force on the jets.

VII. SUMMARY

We have performed 1D and 2D PIC simulations of hydrogen plasma jet propagation and head-on merging. In the parameter regime of the LANL experiment, unmagnetized collisionless shocks could not be detected in the simulation results. The simulations do demonstrate the formation of magnetized (perpendicular) collisionless shocks when $v_j < v_A$. This requires that the jets be immersed in a field ~ 0.1 -1 kG. Simulations predict mach numbers ~ 1 -2 in this parameter range. Non-shock jet interactions as well as ion kinetic effects are also observed in the simulations.

These simulations confirm that the application of an appropriate magnetic field to the LANL experiment is required. Some simple calculations as well as preliminary simulations show that an applied field cannot fully diffuse into the oncoming jets on time scales $< 1 \mu s$. For this reason the jets need to be “born” in the magnetic field or

penetrate into the field by some other mechanism than magnetic diffusion. Larger-scale 2D or 3D simulations require better spatial resolution to avoid numerical difficulties for longer simulation times ($t > 1 \mu\text{s}$).

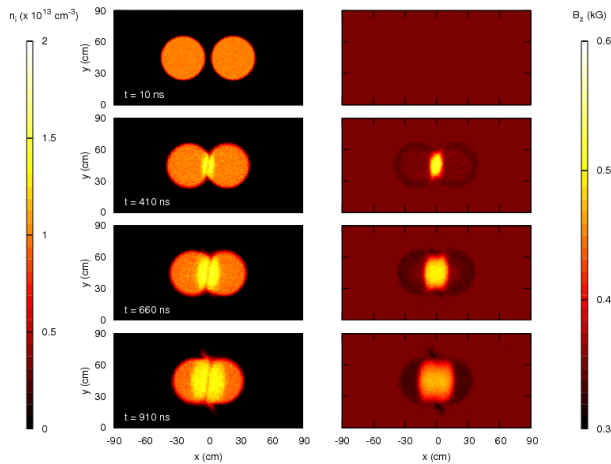


Figure 6. Simulation (2D) of two counter-propagating plasma jets with a 350-G magnetic field in the $+z$ direction.

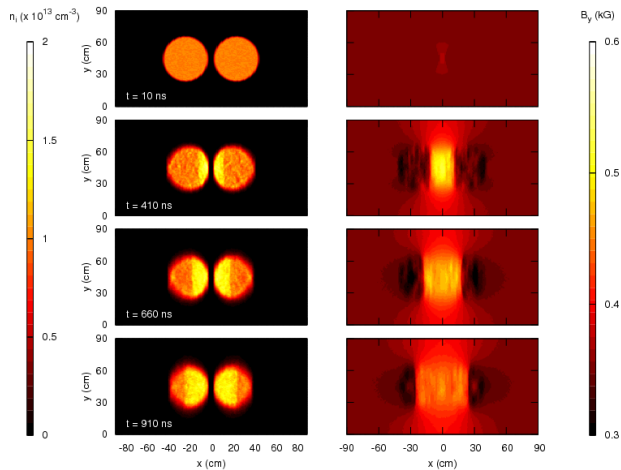


Figure 7. Simulation (2D) of two counter-propagating plasma jets with a 350-G magnetic field in the $+y$ direction.

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