

Influence of finite ion Larmor radius on the dynamics of weakly collisional plasma jets colliding in a magnetic arch

Artem V. Korzhimanov^{1,2} , Roman S. Zemskov¹, Sergey A. Koryagin^{1,2} and Mikhail E. Viktorov^{1,2} 

¹A. V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russian Federation

²Lobachevsky University of Nizhny Novgorod, Nizhny Novgorod, Russian Federation

Corresponding author: Artem V. Korzhimanov, artem.korzhimanov@ipfran.ru

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The effect of the finite ion Larmor radius on the dynamics of two counterstreaming weakly collisional plasma flows in a magnetic field of an arch configuration is considered. Hybrid numerical simulations show that in a system whose dimensions are close to the ion Larmor radius, more intense interaction dynamics is observed and the magnetic arch experiences a significant expansion with the formation of a region with an irregular character of magnetic lines, in which magnetic reconnection processes occur. In this case, the generation of a surface wave of the ion-cyclotron range is observed at the boundaries of the arch. An increase in the scale of the system compared with the ion Larmor radius leads to a transition to the ideal magnetohydrodynamic regime, in which the evolution of the arch occurs much more slowly, and the development of instabilities is not observed.

Key words: plasma nonlinear phenomena, plasma simulation, plasma flows

1. Introduction

The interaction of plasma flows with a magnetic field of an arched configuration is widely encountered both in astrophysics, for example, in solar flares (Masuda *et al.* 1994; Xia *et al.* 2020; Guo *et al.* 2024) and in the magnetosphere of planets (Liu 2020), and in technical devices, for example, in thermonuclear reactors based on magnetic plasma confinement (Kikuchi & Azumi 2012). At the same time, the study of such systems faces a number of technical difficulties that limit the possibilities for diagnosing plasma and fields with the time and spatial resolution necessary for understanding the processes taking place. This makes it valuable to study model processes in simplified laboratory conditions, in which controlled and reproducible generation of plasma flows in given magnetic fields is possible.

Recently, a number of studies have been conducted on the interaction of plasma flows generated in the bases of a magnetic arch (Katz *et al.* 2010; Tripathi & Gekelman 2010; Stenson & Bellan 2012; Zhang, Pree & Bellan 2023). In particular,

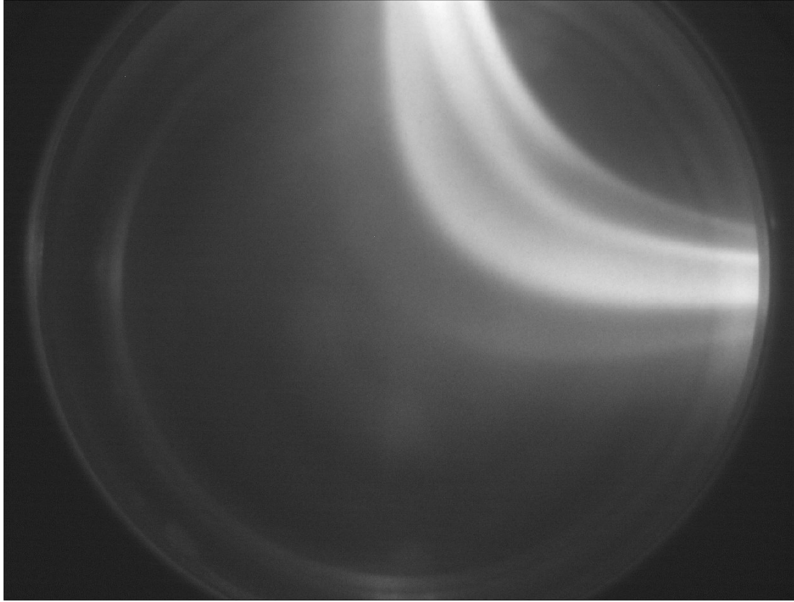


FIGURE 1. An optical plasma glow during collision of two plasma flows registered at the moment of maximum current of a vacuum arc discharge.

our group has developed a laboratory set-up based on an arc discharge plasma injected into a field generated by a pair of pulse coils located at an angle to each other (Viktorov *et al.* 2015, 2019). The plasma flows propagate from the bases of the magnetic arch along magnetic fields and collide in its top. Figure 1 shows a typical glow of the plasma registered in the experiment. The discharge time is $20\ \mu\text{s}$, which is enough to fill the volume of a chamber with a diameter of 20 cm during the discharge. Under typical conditions, the set-up is capable of creating magnetic fields of the order of $B_0 = 10\text{--}100\ \text{mT}$ in the centre of the chamber and plasma flows moving at a velocity of $V_0 \approx 10^6\ \text{cm s}^{-1}$, with a particle concentration in the range of $N_0 = 10^{13}\text{--}10^{16}\ \text{cm}^{-3}$. The electron and ion temperature T_0 in each flow does not exceed several eV, and the energy of directed ion motion $W_{i0} = M_i V_0^2 / 2$ (M_i is the ion mass) is several times higher; for example, for aluminium plasma moving at a velocity of $10^6\ \text{cm s}^{-1}$, $W_{i0} \approx 14\ \text{eV}$. Thus, in this set-up it is possible to observe both sub-Alfvén and super-Alfvén flows: for example, for the same plasma at $B_0 = 100\ \text{mT}$ the magnetic Mach number $M_m = V_0 / V_A$ ($V_A = B_0 / \sqrt{2\mu_0 N_0 M_i}$ is the Alfvén velocity, μ_0 is the magnetic constant) is equal to unity at $N_0 = 1.76 \times 10^{15}\ \text{cm}^{-3}$.

We have previously shown that the transition from the sub-Alfvénic regime to the super-Alfvénic one leads to a significant change in the dynamics of plasma flows in such a system (Korzhimanov *et al.* 2025). In the sub-Alfvénic regime, a more or less stable plasma arch is formed, slowly evolving mainly due to the $\mathbf{E} \times \mathbf{B}$ drift with the formation of a region of oppositely directed magnetic field lines, in which, however, no intense magnetic reconnection is observed. In the super-Alfvénic regime, a partial breakthrough of magnetic lines by plasma flows occurs and a region of turbulent plasma is formed, in which magnetic reconnection processes are more intense and the formation of plasmoids is observed.

Estimates show that in the regime when $M_m \sim 1$, electrons are collisional with a characteristic collision frequency of 10^{10} s^{-1} and a gyrofrequency of the order of 10^9 s^{-1} , while ions are weakly collisional with a characteristic collision frequency of 10^4 s^{-1} and a gyrofrequency of the same order. Thus, the system is subject to the development of ion kinetic instabilities. In particular, the excitation of surface ion-cyclotron waves arising due to the anisotropy of the ion distribution function was observed in the simulation.

This system, however, features a relatively small size of the generated plasma flows. The diameter of the outgoing hole from which the plasma flows out is 2 cm, which is less than or of the same order as the Larmor radius of the ions. Thus, the effects of the finite ion Larmor radius (FILR) become significant for the dynamics of the interaction. Note that the effect of FILR on the processes of interaction of plasma flows with a magnetic field has been the subject of research for many years. In particular, its influence on various instabilities developing in plasma was discussed; examples include drift-cyclotron instability in inhomogeneous plasma (Mikhailovsky 1965), Rayleigh–Taylor instabilities during plasma expansion in a magnetic field (Huba, Lyon & Hassam 1987; Ripin *et al.* 1987; Tang *et al.* 2020) and others (Pokhotelov *et al.* 2004; Ferraro 2007; Landreman, Antonsen & Dorland 2015). The influence of FILR on the type and properties of waves near the ion-cyclotron frequency (Brambilla 1989; Kolesnichenko *et al.* 2023, 2024) was noted. The FILR is also of great importance in the theory of collisionless magnetic reconnection (Grasso *et al.* 2000; Del Sarto *et al.* 2011) and play a significant role in the magnetosphere (Stasiewicz 1993), in the solar atmosphere (Pandey & Wardle 2022) and in the interplanetary plasma (Kubo & Shimazu 2010).

The aim of this work is a numerical study of the influence of FILR on the processes occurring in an experimental set-up in the regime of magnetic Mach numbers of the order of unity. The primary objective of this study was to determine the impact of FILR effects on the plasma expansion across magnetic fields, previously attributed to the $\mathbf{E} \times \mathbf{B}$ drift. Effects of FILR are considered for two principal reasons. First, they enhance the $\mathbf{E} \times \mathbf{B}$ drift velocity and increase the volume of plasma that is effectively polarised (Lindberg 1978). Second, FILR gives rise to an additional expansion mechanism: diffusion across magnetic field lines due to gyroviscosity. We therefore compare the observed expansion rates with theoretical estimates of this gyroviscous diffusion. A secondary aim is to investigate the excitation of ion-cyclotron waves, which were also observed in this system. Given that their dispersion relations are FILR-dependent, we compare their excitation efficiency in plasmas with large and small ion Larmor radii.

2. Numerical methods

For collisional electrons and weakly collisional ions, the optimal modelling method is a hybrid one, in which ions are described in the kinetic collisionless approximation by the particle-in-cell method, and electrons are described as a massless neutralising liquid. To partially take into account the relatively weak kinetic electron effects, electrons are described in the so-called 10-moment approximation, taking into account the pressure tensor evolution equation. Due to the low flow velocities, the electromagnetic field is described in the low-frequency (Darwinian) approximation, in which the displacement current is neglected. Thus, the complete system of equations

to be solved takes the following form (Hesse, Winske & Kuznetsova 1995):

$$\frac{\partial f_i}{\partial t} + \mathbf{v}_i \frac{\partial f_i}{\partial \mathbf{r}} + \frac{Ze}{M_i} (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) \frac{\partial f_i}{\partial \mathbf{v}_i} = 0, \quad (2.1)$$

$$n_e = Zn_i = Z \int f_i(t, \mathbf{r}, \mathbf{v}_i) d\mathbf{v}_i, \quad (2.2)$$

$$\mathbf{V}_i = \frac{1}{n_i} \int \mathbf{v}_i f_i(t, \mathbf{r}, \mathbf{v}_i) d\mathbf{v}_i, \quad (2.3)$$

$$\mathbf{E} = -\mathbf{V}_i \times \mathbf{B} + \frac{1}{en_e} (\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{P}), \quad (2.4)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad (2.5)$$

$$\mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B}, \quad (2.6)$$

$$\mathbf{V}_e = -\frac{1}{en_e} \mathbf{j} + \mathbf{V}_i, \quad (2.7)$$

$$\begin{aligned} \frac{\partial \mathbf{P}}{\partial t} + \mathbf{V}_e \cdot \nabla \mathbf{P} = & -\mathbf{P} \nabla \cdot \mathbf{V}_e - \mathbf{P} \cdot \nabla \mathbf{V}_e - (\mathbf{P} \cdot \nabla \mathbf{V}_e)^T \\ & - \frac{e}{m_e} [\mathbf{P} \times \mathbf{B} + (\mathbf{P} \times \mathbf{B})^T]. \end{aligned} \quad (2.8)$$

Here e and m_e are the elementary charge and mass of an electron, Z is the ionisation multiplicity of ions, $n_{e,i}(t, \mathbf{r})$ are the concentrations of electrons and ions, respectively, $\mathbf{V}_{e,i}(t, \mathbf{r})$ are the average (hydrodynamic) velocities of electrons and ions, $\mathbf{P}$ is the electron pressure tensor, ∇ is the del (nabla) vector differential operator and $(\cdot)^T$ denotes the tensor transpose. Note that the kinetic description of the ion dynamics explicitly takes into account the finiteness of their Larmor radius, while its influence on the plasma dynamics as a whole is provided by the second and third terms in the generalised Ohm law (2.4), while the term $\mathbf{j} \times \mathbf{B}$, called the Hall term, is responsible for the effects associated with the directed velocity of ions relative to electrons and the term $\nabla \cdot \mathbf{P}$ is responsible for the effects associated with their thermal velocities. These terms are responsible for the effects of non-ideal magnetohydrodynamics. In the generalised Ohm equation, we neglected the term associated with the electron inertia, which is justified in the case of a sufficiently hot plasma, when the plasma beta $\beta > m_e/M_i$ (which is equivalent to the smallness of the electron inertial length compared to the ion Larmor radius), which is certainly satisfied under the conditions of our set-up.

Hybrid modelling was performed using the AKA code (Sladkov, Smets & Korzhimanov 2020). This code simulates the system (2.1)–(2.8) by means of the particle-in-cell method for the ion kinetic equation, second-order finite-difference predictor–corrector scheme for electromagnetic fields and subcycling explicit scheme for pressure tensor evolution. It was tested in a model problem for analysing the magnetic reconnection process in the Harris layer on electron spatial scales

(Sladkov *et al.* 2021), in a problem on the long-term dynamics of the Weibel instability (Sladkov & Korzhimanov 2023), as well as in modelling experiments on laser ablation of plasma in an external magnetic field (Bolaños *et al.* 2022; Burdonov *et al.* 2022; Sladkov *et al.* 2024; Zemskov *et al.* 2024).

The simulations were performed in two-dimensional geometry with all three components of electric and magnetic fields as well as particle velocities being taken into account. The parameters of simulations were chosen to be close to the conditions of the real experiment. The simulation area was $20 \text{ cm} \times 20 \text{ cm}$, the plasma flow diameter was 2 cm , the ion concentration in the plasma flows was 10^{15} cm^{-3} , the plasma was assumed to be fully ionised and consist of singly ionised aluminium, the plasma flow velocity was $V_0 = 10^6 \text{ cm s}^{-1}$ and the electron and ion temperature was assumed to be initially zero. The flows were injected from spots positioned 2 cm away from the boundaries. The boundaries were supposed to be open (absorptive) for both particles and fields. The total simulation time was about $60 \mu\text{s}$. The external magnetic field was set based on electromagnetic calculations for the known geometry of real coils. The field strength in the bases of the arch was $B_0 = 80 \text{ mT}$.

With the specified parameters, the ion inertial length $d_0 = c\sqrt{\varepsilon_0 M_i / e^2 N_0}$ (ε_0 is the electric constant) is about 1.2 cm , the ion Larmor radius is of the same scale as at magnetic Mach numbers of about 1 and the plasma jet diameter is 2 cm . This leads to dynamics features associated with the FILR. To reveal these features in the simulations, a series of calculations were also carried out for larger scales of the system: in a $120 \text{ cm} \times 120 \text{ cm}$ box and for a plasma jet diameter of 12 cm .

In the first approximation, the effects of FILR can be described as an anomalous viscosity, the so-called gyroviscosity, characterised by the kinematic viscosity coefficient $\nu = V_{i\perp}^2 / 2\Omega_i$, where $V_{i\perp}$ is the thermal velocity of ions across the magnetic field and $\Omega_i = ZeB/M_i$ is the ion gyrofrequency. The Reynolds number can then be estimated as $R = V_i L / \nu = 2(V_i / V_{i\perp})(L / r_i)$, where V_i is the ion velocity, L is the scale of the inhomogeneity and r_i is the ion Larmor radius. Note that in the case of weak curvature of magnetic lines, so that their radius of curvature is $\varrho_B \gg r_i$, the transverse velocity of ions changes adiabatically, and in a quasi-homogeneous field remains constant; thus, for supersonic flows $V_i / V_{i\perp} \sim 5$. However, in strongly curved fields, for which $\varrho_B \lesssim r_i$, the longitudinal velocity quickly turns into transverse velocity, and thus $V_i / V_{i\perp} \sim 1$.

For the first case studied (conditions close to those of the experimental set-up) $\varrho_B \approx 10 \text{ cm}$ and $r_i \approx 1 \text{ cm}$; thus, the curvature of the magnetic lines is relatively small, although significantly higher than in the second case, for which the ion Larmor radius is the same, and $\varrho_B \approx 60 \text{ cm}$. As a scale of inhomogeneity, we can take the radius of the plasma flows: $L \approx 1 \text{ cm}$ in the first case and $L \approx 6 \text{ cm}$ in the second. Thus, the Reynolds number in the first case is $R \approx 10$ and in the second case is $R \approx 60$.

3. Simulation results

At first, the sub-Alfvénic regime was investigated, in which the magnetic Mach number was slightly less than unity (the plasma flow pressure was lower than the magnetic pressure). The evolution of the plasma density and magnetic field is shown in figure 2.

Due to the spatial scales being increased by six times in the second case, the given time moments are six times greater than the time moments in the first case. As we can see, the the interaction has noticeable differences. For large-scale flows, a

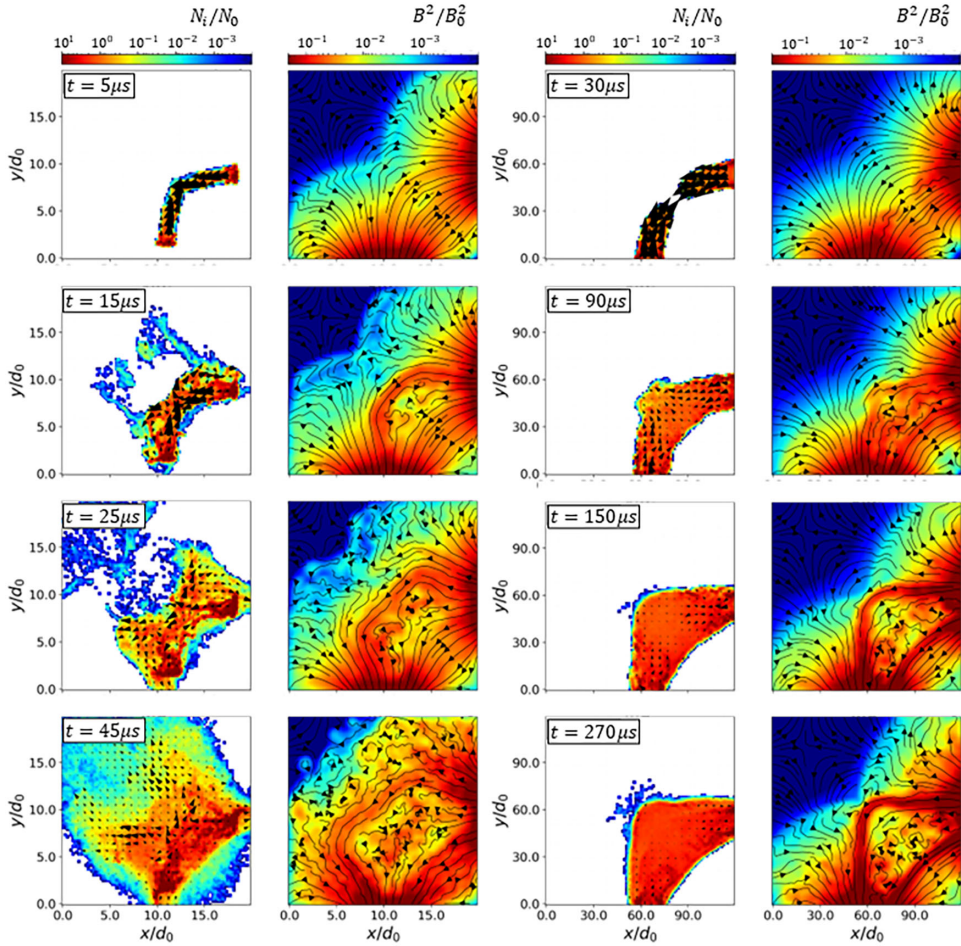


FIGURE 2. Ion concentration (left) and magnetic pressure (right) for calculations with small-scale (left column) and large-scale (right column) systems. The lines represent the in-plane component of magnetic field $\mathbf{B}_{xy}$. Concentration is normalised to the initial concentration $N_0 = 10^{15} \text{ cm}^{-3}$, magnetic pressure is normalised to the initial pressure of the plasma flow ($B_0 = 80 \text{ mT}$), coordinates are normalised to the ion inertial length $d_0 = 1.18 \text{ cm}$, for reference inverse ion gyrofrequency $\Omega_i^{-1} = 0.1 \text{ } \mu\text{s}$.

calmer, quasi-stationary interaction pattern is observed. Both ions and electrons are magnetised and the general dynamics is of magnetohydrodynamic nature. A stable plasma arch is formed, which practically does not evolve in time. For a small-scale system, the formed arch is not stationary, a part of the plasma escapes it and its fairly rapid expansion is observed. Let us estimate the time required for such expansion due to gyroviscosity. We consider the diffusion coefficient to coincide with the kinematic viscosity coefficient: $D \approx \nu$. The expansion time can then be estimated as $T_D \approx \mathcal{L}^2/D = R(\mathcal{L}/L)(\mathcal{L}/r_i)\Omega_i$, where $\mathcal{L}$ is the distance over which the plasma has expanded. For the first case, we have $\mathcal{L} \approx 10 \text{ cm}$ and $T_D \approx 1000\Omega_i$, which significantly exceeds the simulation time. Thus, the plasma expansion in this case cannot be explained by the gyroviscous model alone, but occurs mainly due to the $\mathbf{E} \times \mathbf{B}$

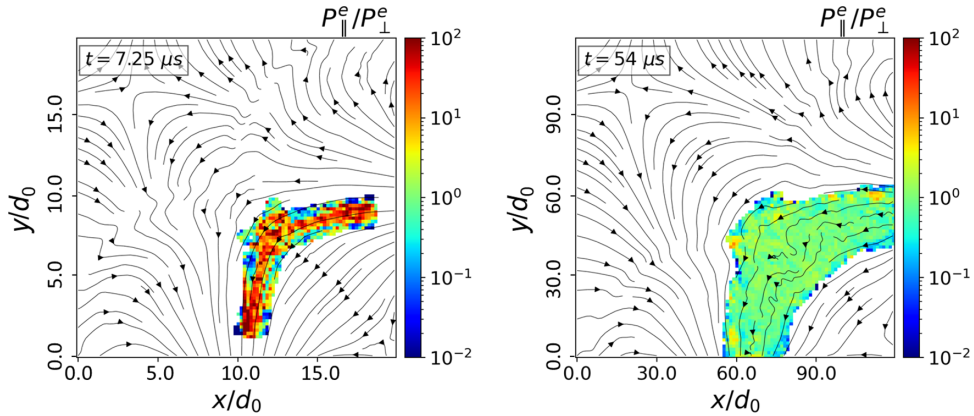


FIGURE 3. The ratio of the longitudinal component of the electron pressure tensor with respect to the magnetic field to the transverse component in the calculation plane. On the left is a calculation with the small-scale system, on the right is a calculation with the large-scale system.

drift. And as expected the drift-driven plasma expansion is much more pronounced in the small-scale system.

Note also that in the small-scale system, a magnetic field region with irregular magnetic lines is formed inside the arch, which indicates the possibility of magnetic reconnection processes occurring in it. In addition, in this case, some filamentation of the plasma density is observed, which we associate with the development of Weibel-type instability due to the anisotropy of the electron pressure tensor. Indeed, from figure 3 it is evident that the anisotropy of the electron pressure in this case is significant and reaches tens, while for large-scale flows it is close to unity.

Another feature of the system under study is the excitation of ion-cyclotron surface waves at the plasma tube boundary. Figure 4 shows that this wave is clearly seen for a small-scale system and has an elliptical polarisation with a predominantly xy component (i.e. this is an Alfvén-type wave). These waves can be excited either as a result of the development of instability associated with the anisotropy of the ion component pressure (Sagdeev & Shafranov 1961) or due to specific instabilities associated with FILR (Kolesnichenko *et al.* 2023, 2024). The latter explanation is supported by the fact that for a large-scale system the wave amplitude is much weaker, and its z component is not visible at all against the background of strong fields caused by the diamagnetic effect (with a spatial scale of the order of the ion Larmor radius). A more detailed study of these waves in our system, however, is beyond the scope of this paper and will be considered separately.

Thus, the small-scale system exhibits significantly less stable behaviour, and its evolution is accompanied by intensive development of instabilities of kinetic nature.

Let us now consider the case of denser flows, for which the magnetic Mach number exceeds unity (the flow pressure is higher than the magnetic pressure). The corresponding results are shown in figure 5.

As noted in earlier studies, the interaction process in this case is noticeably more intense, and a partial rupture of magnetic lines by flows is observed. In the small-scale case, the formation of structures with closed magnetic lines – plasmoids – is

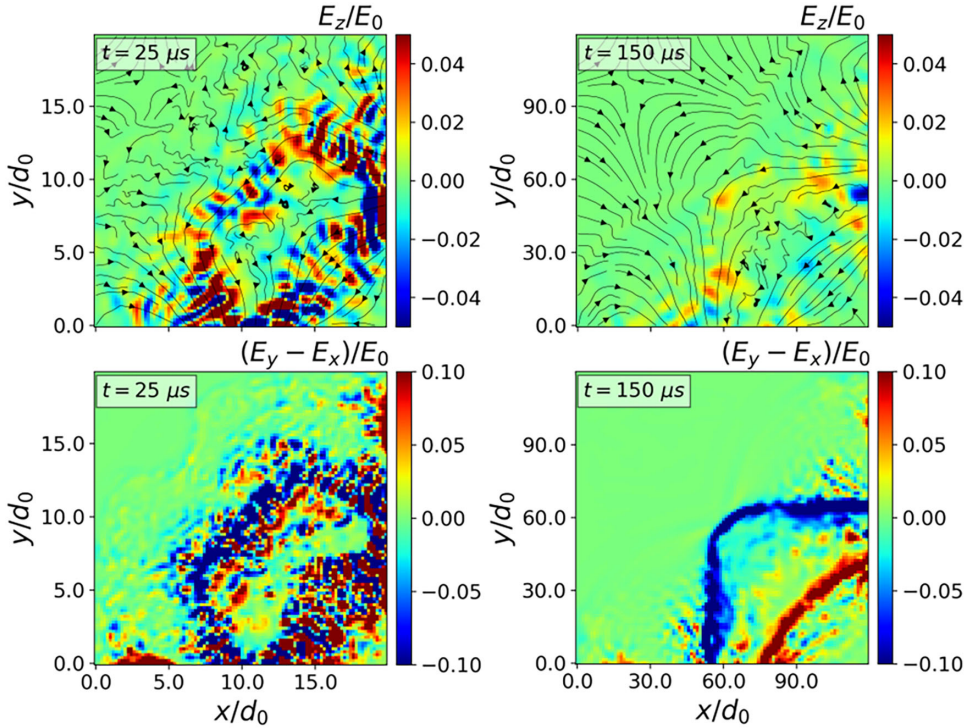


FIGURE 4. The z (top) and xy (bottom) components of the electric field for small-scale (left) and large-scale (right) systems. Arrows indicate the magnetic field. The electric field is normalised to $E_0 = V_0 B_0 = 25 \text{ V cm}^{-1}$.

observed in the expanded arch. Nevertheless, for a large-scale system, even in this case, no significant expansion of the arch is observed, although its shape is strongly deformed by the plasma pressure, and plasmoid-like structures are also observed inside the plasma.

4. Conclusions

Thus, the comparability of the system scales with the ion scales in the case under study is of fundamental importance for observing the intense dynamics of interaction and the development of kinetic-type instabilities. This coincides with the results of earlier studies, which noted that the FILR leads to an increased rate of existing instabilities (Huba *et al.* 1987) and to the emergence of new ones (Mikhailovsky 1965). It has also recently been shown that in the arch configuration, a decrease in the arch size to the ion scale leads to the development of instabilities accompanied by intense X-ray emission of accelerated electrons (Zhang *et al.* 2023). This allows us to expect non-thermal high-frequency radiation in our experimental set-up, likely in the electron-cyclotron range which will be a possible subject of our future research.

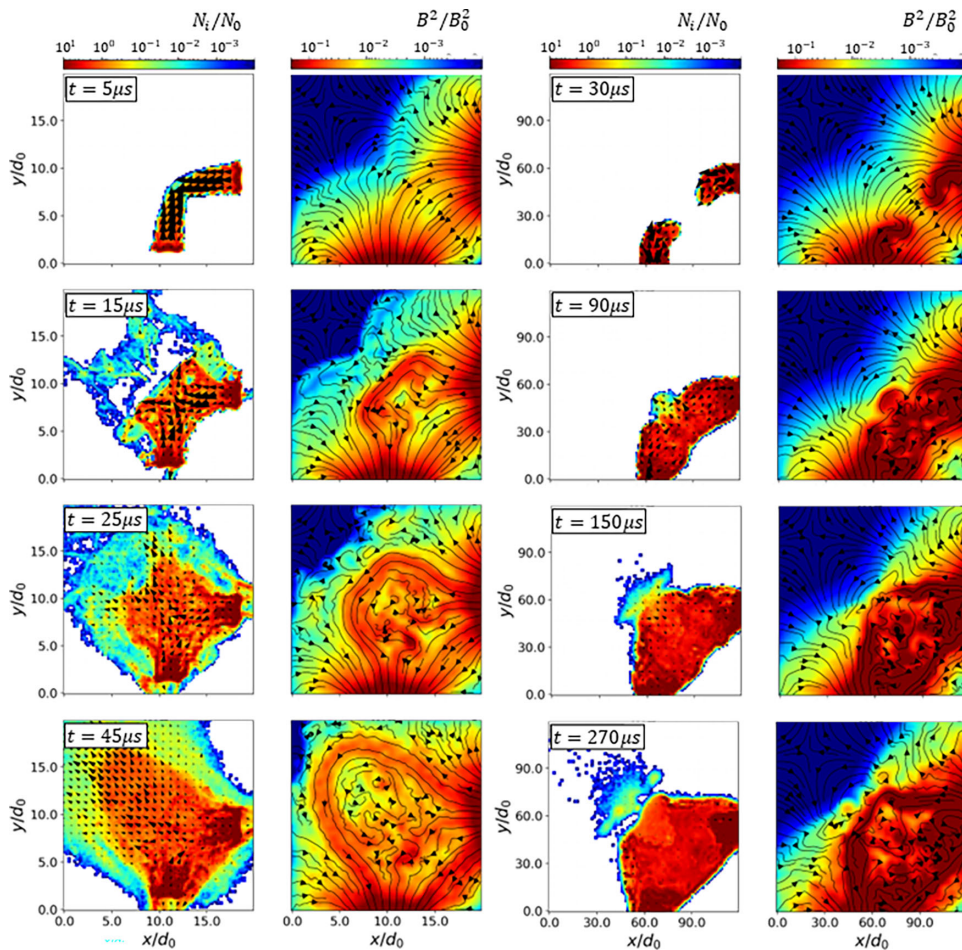


FIGURE 5. The same as in figure 2, but for plasma flows five times denser.

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Declaration of interests

The authors report no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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