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1 Numerical methods and macroscopic models of  
2 magnetically confined plasmas for propulsion

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5 **Abstract**

6 In this paper a hierarchy of macroscopic plasma models is derived  
7 for the numerical study of plasma thrusters. This derivation outlines  
8 the multi-scale nature of the problem and the difficulty for numerical  
9 methods to address efficiently this challenge. A specific focus is made on  
10 quasi-neutral models built on the anisotropic equations of the particles  
11 transport. A numerical method is proposed for this class of problems of-  
12 fering an accuracy unrelated to the anisotropy strength without resorting  
13 to the approximation of equipotential magnetic field lines.

14 **Keywords** Anisotropic equation, Plasma Physics, Asymptotic-Preserving schemes.

15 **1 Introduction**

16 The simulation of plasma propulsion devices [6, 38] represents a significant chal-  
17 lenge for the design of efficient numerical methods. This is due to the multi-

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1 scale nature of plasma physics [15] in general and specifically in the context of  
2 this application. We consider in this paper low temperature magnetized plas-  
3 mas typical of those of ion sources for space propulsion (e.g. Hall thrusters  
4 also called Stationary plasma thrusters, gridded ion thrusters, cusp-field plasma  
5 thrusters etc... [6],[38]). The plasma evolution may be described by kinetic  
6 models for both the electrons and the ions for the most refined descriptions  
7 [14, 9, 29, 5, 7, 26]. Hybrid models [3] rely on a coarser representation of the  
8 electrons, this species being described by a fluid model. Finally the ions may  
9 also be described by a fluid model [23, 22, 36]. This latter class of models  
10 will be specifically investigated in the present work. Though they offer a quite  
11 coarse plasma description, they give access to reach enough physics and with  
12 an incomparable computational efficiency compared to kinetic descriptions.

13 The multi-scale nature of the problem exceeds the only questions of the ki-  
14 netic or macroscopic modellings of the plasma. Generally it also encompasses  
15 the quasi-neutrality of the plasma and the small scales attached to the electron  
16 inertia. The question related to the quasi-neutrality has received a lot of at-  
17 tention including the treatment of local breakdowns [12, 13, 18, 16, 11, 1, 2].  
18 Quasi-neutral models filter out the small scales related to charge separations,  
19 namely the Debye length and the plasma period. In regions of large plasma  
20 densities, these two scales are small compared to that of the device operation.  
21 It is therefore interesting to filter out these scales from the equations to derive  
22 an efficient simulation tool. In the context, of magnetically confined plasmas,  
23 this class of models introduces a specific difficulty. Due to the intense magneti-  
24 sation of the plasma, the equations are severely anisotropic which represents a  
25 major difficulty for numerical methods to produce accurate approximations of  
26 the electric field. This issue is identified as the main bottleneck for the derivation  
27 of numerical methods based on quasi-neutral models ([30, Sec. III]).

28 The present work is first dedicated to the derivation of a hierarchy of macro-  
29 scopic (fluid) models for strongly magnetized plasmas. This study is conducted  
30 in order to clarify the different assumptions embedded in the models used in  
31 the context of these plasmas and, more specifically, in the context of electric  
32 propulsion: plasmas are cold, partially ionized, the ions being non magnetized.  
33 This work is restricted to two dimensional geometries containing the magnetic  
34 field lines (*i.e.* there is no magnetic field component perpendicular to the two  
35 dimensional simulation domain), the aim being the capture of steady states. In  
36 particular, the physics developing in the  $E \times B$  direction [35] is out of the scope  
37 of the present investigations. A derivation of these models, by means of the  
38 asymptotic analysis, is therefore proposed together with an emphasis of how  
39 these models relate to each other.

40 In a second part, a more specific attention is paid to the numerical approxi-  
41 mation of anisotropic problems providing the electric potential in quasi-neutral  
42 models. The difficulty here stems from two different aspects of the problem.  
43 The first one is related to the loss of precision of numerical approximations  
44 with coordinates and meshes misaligned to the anisotropy (magnetic field) di-  
45 rection [23]. This is analyzed in [41] and explained by an amplification of the  
46 discretization error by the large heterogeneity of the parallel and perpendicular

1 transport coefficients. Furthermore, the condition number of the system matrix  
 2 stemming from the discretization of the anisotropic problem may increase with  
 3 the anisotropy strength, depending on the boundary conditions imposed at the  
 4 magnetic field line ends. Different workarounds are proposed to circumvent this  
 5 difficulty. The limit problem, obtained by assuming an infinite anisotropy, is  
 6 proposed to compute the electric field approximation in [23]. This amounts to  
 7 considering the magnetic field lines as equipotential for the electric potential.  
 8 Field aligned approaches come naturally into play to address the loss of pre-  
 9 cision originating from the mesh misalignment. This is the path followed for  
 10 instance in [33, 32] (in the framework of electric propulsion, see also [39] for  
 11 ionospheric plasma simulations). Nonetheless, these methods are difficult to  
 12 extend to complex magnetic field geometries such as cusp-shaped field [25, 37]  
 13 considered within this document. An original numerical method, free from this  
 14 constraint, is proposed in [27, 8, 28]. It relies on an hyperbolic formulation  
 15 of the anisotropic problem satisfied by the electric potential. The solution of  
 16 the anisotropic problem is approximated by the steady state of a pseudo-time  
 17 dependant system. The convergence time to this steady state is roughly pro-  
 18 portional to the anisotropy strength: the number of pseudo-time iterations is  
 19 observed to scale as  $\varepsilon^{-0.7}$  [27, 8].

20 In recent studies, the derivation of efficient numerical methods for anisotropic  
 21 problems has been addressed thanks to asymptotic-preserving schemes [17], ini-  
 22 tially for field aligned coordinates, this requirements being unnecessary in sub-  
 23 sequent developments [16, 19, 20, 40]. These numerical methods are designed to  
 24 capture the limit regime when  $\varepsilon \rightarrow 0$ . This avoids the blow-up of the condition  
 25 number of the system matrix and preserve the accuracy of the approximation  
 26 for increasing anisotropy strength. This class of numerical methods is imple-  
 27 mented in the context of magnetically confined plasmas in a range of parameters  
 28 representative of electric propulsion. A new augmented Micro-Macro method is  
 29 introduced within this document with the aim to correct the loss of symmetry  
 30 of the so-called inflow Micro-Macro method [19].

31 The paper is organized in three sections. The first section is devoted to the  
 32 derivation of the model hierarchy. It is designed to represent the evolution of  
 33 an isothermal low temperature plasma confined by an intense magnetic field.  
 34 The models considered within this hierarchy are fluid models originating from a  
 35 bi-fluid plasma representation, coupled to Poisson equation providing the elec-  
 36 trostatic potential. Different reduced models are then introduced by letting  
 37 asymptotic parameters vanish, to recover the quasi-neutrality assumption, the  
 38 massless approximation of the electron and eventually the infinite anisotropy  
 39 regime. In the second section, the difficulty stemming from the discretization  
 40 of anisotropic problem is addressed. The set of equations considered for the  
 41 simulation of magnetically confined plasma is specified including the geometry  
 42 of the cusp-shaped magnetic field together with a set of boundary conditions  
 43 representing the inter-electrode chamber into which the plasma is confined. The  
 44 loss of precision of numerical methods is outlined and a new augmented Micro-  
 45 Macro method is introduced to address this issue. Numerical investigations are  
 46 proposed within the third section. A analytic framework is proposed in order to

1 assess the effectiveness of the augmented Micro-Macro method. The advantage  
 2 of this test case comes from the fact that an exact solution can be manufactured  
 3 (analytically) providing a reference exact solution against which the numerical  
 4 approximation can be compared. This procedure permits the validation of the  
 5 augmented Micro-Macro method implemented on the complete model for the  
 6 simulation of the plasma confinement by a cusp-shaped magnetic field. The  
 7 loss of symmetry of the numerical approximation carried out thanks to the in-  
 8 flow Micro-Macro method is outlined thanks to these numerical experiments, in  
 9 contrast the approximations provided by the augmented Micro-Macro method  
 10 respect the expected symmetry properties.

## 11 **2 A hierarchy of fluid models for plasma propul-** 12 **sion.**

### 13 **2.1 Bi-fluid isothermal plasma modelling coupled to the** 14 **Poisson equation**

15 The purpose here is to derive a model problem relevant for the simulation of  
 16 the plasma of ion sources for space propulsion (termed as "plasma thrusters" in  
 17 the following) in a simplified, but representative, context. This derivation is or-  
 18 ganized in a hierarchy of models outlining the multi-scale nature of the problem  
 19 and hereby the difficulty to derive efficient numerical methods for these mod-  
 20 els. This hierarchy is constructed by letting dimensionless parameters vanish,  
 21 deriving by this means reduced models.

The starting point is a set of equations for both the ions and the electrons  
 coupled to Maxwell's equations to account for the computation of the electro-  
 magnetic field. The properties of the neutral gas are assumed to be known in  
 this simplified problem. Let  $(m_\alpha, n_\alpha, u_\alpha, T_\alpha)$  be the mass, density, mean veloc-  
 ity and temperature of the species  $\alpha$ , with  $\alpha = i, e$  for the ions or the electrons.  
 Assuming that both the electron and ion temperatures are constant and consid-  
 ering mono charged ions, the plasma evolution may be described thanks to  
 the following sets of equations

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha u_\alpha) = S, \quad (1a)$$

$$m_\alpha \left( \frac{\partial n_\alpha u_\alpha}{\partial t} + \nabla \cdot (n_\alpha u_\alpha \otimes u_\alpha) \right) + \nabla (n_\alpha k_B T_\alpha) = q_\alpha n_\alpha (E + u_\alpha \times B) - m_\alpha n_\alpha \nu_\alpha u_\alpha, \quad (1b)$$

22 s  $q_\alpha$  being the charge of the particle,  $q_e = -e$  and  $q_i = e$  with  $e$  the elementary  
 23 charge,  $k_B$  the Boltzmann constant, the tensor product of two vectors  $u$  and  $v$   
 24 is denoted  $u \otimes v$ .

25 Different collision processes are accounted for:  $\nu_\alpha$  is the collision frequency of the  
 26 specie  $\alpha$  against the neutrals, the neutral being at rest and,  $S$  is the plasma  
 27 density created or destroyed by ionisation or recombination. Note that the  
 28 ion-electron collisions are discarded in both the electronic and ionic equations.

1 The changes in the electromagnetic field are driven by Maxwell's equation  
 2 however in an electrostatic approximation, the magnetic field induced by the  
 3 particle motion being assumed negligible compared to the external one. In the  
 4 end, the charged particles are coupled by the Poisson equation

$$-\Delta\phi = \frac{e}{\varepsilon_0}(n_i - n_e), \quad (2)$$

5  $\varepsilon_0$  being the vacuum permittivity. The electric field is deduced from the elec-  
 6 trostatic potential  $\phi$  thanks to

$$E = -\nabla\phi. \quad (3)$$

7 The set of equations (1–3) define the basis of the hierarchy of (isothermal)  
 8 models aimed at representing the operation of plasma thrusters.

## 9 **2.2 The dimensionless bi-fluid-Poisson system**

10 This hierarchy of models is derived thanks to the introduction of asymptotic  
 11 parameters, introduced in the equations by working with non dimensional quan-  
 12 tities. First, some physical quantities are introduced. The cyclotron frequency  
 13  $\omega_{c,\alpha}$  the mobility  $\mu_\alpha$ , the Hall parameter  $\mathcal{H}_\alpha$  for the species  $\alpha$  defined as

$$\omega_{c,\alpha} = \frac{e|B|}{m_\alpha}, \quad \mu_\alpha = \frac{e}{m_\alpha\nu_\alpha}, \quad \mathcal{H}_\alpha = \mu_\alpha\|B\|, \quad (4a)$$

14 and finally the (electronic) Debye length

$$\lambda_D^2 = \frac{\varepsilon_0 k_B T_e}{e^2 n_e}. \quad (4b)$$

15 Let  $\bar{x}, \bar{t}$  be the typical length and time scales, these parameters are chosen to  
 16 capture the flow of the plasma, the electron and ion mean velocity being assumed  
 17 comparable and denoted  $\bar{u}$ . This entails to the following scaling relation

$$\bar{u} = \frac{\bar{x}}{\bar{t}}. \quad (5a)$$

18 The plasma is assumed to be close to quasi-neutrality, with comparable electron  
 19 and ion densities  $\bar{n}_i = \bar{n}_e = \bar{n}$ . The typical temperature of the species  $\alpha$  is  
 20 denoted  $\bar{T}_\alpha$  while  $\bar{\nu}_\alpha$  is the typical collision frequency (against neutrals). The  
 21 simple scaling relation proposed in [24, 4] for the collision frequencies is resumed  
 22 for this analysis, with

$$\bar{\nu}_e = \sqrt{\frac{\bar{T}_e m_i}{\bar{T}_i m_e}} \bar{\nu}_i. \quad (5b)$$

23 The electromagnetic field scales are denoted  $\bar{E}, \bar{B}$  for the electric and magnetic  
 24 components, with  $\bar{\phi} = \bar{x}\bar{E}$ . Finally, the typical scale of the ionization term is  
 25 defined by  $\bar{S} = \bar{n}/\bar{t}$ .

Non dimensional variables are used to write the equations, with for instance  $n_i = \bar{n}n'_i$ , the primed quantities being dimensionless. The system (1–2) is recast into

$$\frac{\partial n'_i}{\partial t'} + \nabla' \cdot (n'_i u'_i) = S', \quad (6a)$$

$$M_i^2 \left( \frac{\partial n'_i u'_i}{\partial t'} + \nabla' \cdot (n'_i u'_i \otimes u'_i) \right) + \theta^{-1} \nabla' (n'_i T'_i) = \eta (n'_i E') \\ + \bar{\mathcal{H}}_i M_i^2 \kappa_i (n'_i u'_i \times B') - \theta^{-1/2} M_i^2 \kappa_i (\nu'_i n'_i u'_i), \quad (6b)$$

for the ions, together with

$$\frac{\partial n'_e}{\partial t'} + \nabla' \cdot (n'_e u'_e) = S', \quad (7a)$$

$$\frac{1}{\kappa_e} \left( \frac{\partial n'_e u'_e}{\partial t'} + \nabla' \cdot (n'_e u'_e \otimes u'_e) \right) + \frac{1}{M_e^2 \kappa_e} \nabla' (n'_e T'_e) = -\frac{\eta}{M_e^2 \kappa_e} (n'_e E') \\ - \bar{\mathcal{H}}_e (n'_e u'_e \times B') - \nu'_e n'_e u'_e, \quad (7b)$$

for the electrons, coupled to the Poisson equation

$$-\eta \lambda^2 \Delta \phi' = n'_i - n'_e, \quad (8a)$$

$$E' = -\nabla' \phi'. \quad (8b)$$

- 1 The system (6-8) is written thanks to the dimensionless parameters defined in Table 1. Note that, the electric energy being measured with respect to the elec-

Table 1: Definition of the dimensionless parameters.

$m^2 = \frac{m_e}{m_i}$	electron to ion mass ratio;
$\lambda = \frac{\lambda_D}{\bar{x}}$	scaled Debye length;
$\theta^2 = \frac{\bar{T}_e}{\bar{T}_i}$	electron to ion temperature ratio;
$\kappa_\alpha = \bar{\nu}_\alpha \bar{t}$	number of collisions against neutral during a typical time;
$\bar{\mathcal{H}}_\alpha = \bar{\mu}_\alpha \bar{B} = \frac{\bar{\omega}_{c,\alpha}}{\bar{\nu}_\alpha}$	Hall parameter;
$\Omega_{c,\alpha} = \omega_{c,\alpha} \bar{t}$	number of cyclotron rotations during a typical time;
$M_\alpha^2 = \frac{m_\alpha \bar{u}^2}{k_B \bar{T}_\alpha}$	squared Mach number for species $\alpha$ ;
$\eta = \frac{e \bar{x} \bar{E}}{k_B \bar{T}_e}$	electric energy related to the electronic internal energy.

- 2  
3 tron internal energy by means fo the parameter  $\eta$  definition, scales attached to  
4 the electrons (temperature) are introduced into the dimensionless ionic equa-  
5 tions (parameters  $\theta$  and  $\eta$ ).

## 1 2.3 Derivation of reduced models

### 2 2.3.1 A review of models for magnetized low temperature plasmas

The regimes investigated herein share some properties. First, the electric energy magnitude is assumed to match that of the electronic internal energy, yielding  $\eta = 1$ . Second, the temperature of the electron is larger than the ionic temperature with  $\theta > 1$ . This allows to neglect the pressure in the ionic flux equation. The ionic internal and kinetic energies are assumed to have comparable scales, while the collisions of ions against neutral are unimportant in explaining the evolution of this species. Finally, the ions are non magnetized. These assumptions give rise to the following scaling relations

$$\eta = 1, \quad \theta > 1, \quad M_i^2 \sim 1, \quad (9a)$$

$$\kappa_i \lesssim 1, \quad \bar{\mathcal{H}}_i \lesssim 1. \quad (9b)$$

Note that, the relations (9b) yield  $\omega_{ci}\bar{t} < 1$  or equivalently, the scale of the velocity being defined by Eq. (5a),  $\bar{u}/(\bar{x}\omega_{ci}) > 1$ . The typical ionic Larmor radius exceeds the typical length scale, hence the demagnetization of the ions. The equations governing the evolution of this species may be reduced to

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i u_i) = S, \quad (10a)$$

$$\frac{\partial n_i u_i}{\partial t} + \nabla \cdot (n_i u_i \otimes u_i) = n_i E, \quad (10b)$$

while the electronic macroscopic properties obey the system

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e u_e) = S, \quad (11a)$$

$$\frac{1}{\kappa_e} \left( \frac{\partial n_e u_e}{\partial t} + \nabla \cdot (n_e u_e \otimes u_e) \right) = -\frac{1}{M_e^2 \kappa_e} \left( \nabla (n_e T_e) + n_e E \right) - \bar{\mathcal{H}}_e (n_e u_e \times B) - \nu_e n_e u_e, \quad (11b)$$

coupled to Poisson equation

$$-\lambda^2 \Delta \phi = n_i - n_e, \quad (12a)$$

$$E = -\nabla \phi. \quad (12b)$$

3 Note that, for conciseness, the primes are omitted to identify the dimensionless  
4 quantities in Eqs. (10–12) and thereafter.

5 The hierarchy of fluid models is illustrated on Fig. 1. The bi-fluid Euler-  
6 Poisson model stands at the root of this hierarchy. This model is mainly used for  
7 the simulation of the plasma in regions of low density, predominantly in sheaths  
8 created in the vicinity of walls (see for instance [1, 2] for one dimensional non  
9 magnetized low temperature plasma simulations). One stream emerging from  
10 the root of this hierarchy is specific to quasi-neutral plasma descriptions. These  
11 models describe the evolution of the plasma with large densities on scales where

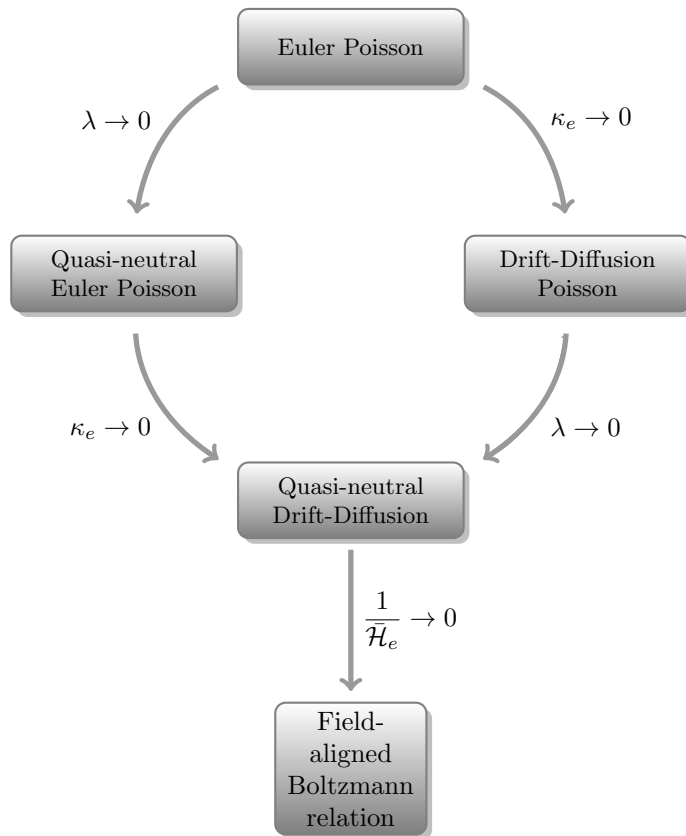


Figure 1: Hierarchy of (isothermal) fluid models.

1 the ions and the electrons may not be distinguished. The second stream is ded-  
 2 icated to plasma descriptions on the ionic time scale. These models follow the  
 3 plasma bulk evolution associated to the massive ions, the fast scales attached  
 4 to the electron being filtered out from the equations. Both streams are merging  
 5 into a model embedding both the quasi-neutrality and the drift approxima-  
 6 tion for the electrons. Reduced models derived on these two assumptions are  
 7 the most widely used for the simulation on large scales in the context of low  
 8 temperature plasmas [36, 22, 1, 33, 32]. The last reduction is related to the  
 9 so-called Boltzmann relation for the electrons, used very often throughout in  
 10 plasma physics, in particular for low-pressure (low-collisional), non-magnetized  
 11 plasmas or plasma sheaths. In the present framework, it is specific to the large  
 12 magnetization of the electrons. It relies on the assumption that the electron  
 13 collision frequency is small compared to cyclotron frequency. This leads to a  
 14 force balance along the magnetic field lines in which the drift term, originating  
 15 from the collisions with neutral, has vanished. This accounts for a departure

1 from the drift regime to the so-called Boltzmann relation in the direction of the  
 2 magnetic field. This model is implemented in [23] for the simulation of plasma  
 3 thrusters.

This hierarchy of fluid models is derived owing  $\mathbf{m} \ll 1$ , the smallness of this  
 parameter together with Eqs. (9) yields the following scaling relations

$$\frac{1}{\kappa_e} = \frac{\mathbf{m}}{\theta} \frac{1}{\kappa_i} \ll 1, \quad \frac{1}{M_e^2 \kappa_e} = \frac{\theta}{\mathbf{m}} \frac{1}{M_i^2 \kappa_i} \gg 1, \quad \frac{1}{\bar{\mathcal{H}}_e} = \frac{1}{\mathbf{m}\theta} \frac{1}{\bar{\mathcal{H}}_i} \ll 1, \quad (13)$$

4 from which originates the reduced models previously mentioned and formally  
 5 derived in the next sections.

### 6 2.3.2 Drift-diffusion regime for the electrons

This regime amounts to letting  $M_e^2 \rightarrow 0$  but with finite values for both ( $M_e^2 \kappa_e$ )  
 and  $\mathcal{H}_e$ . The low Mach regime of the electrons entails the assumption that  
 collisions with neutrals are frequent ( $1/\kappa_e \rightarrow 0$ ). This regime prevails in the  
 plasma bulk, where the mean velocity of the electrons roughly matches that of  
 the ions. The low electron to ion mass ratio is therefore at the origin of the  
 low Mach regime for the electrons (assuming  $M_i^2 \sim 1$ ). Nonetheless, this is not  
 representative of the dynamics developing in the entire domain. In particular,  
 a different regime characterizes electrostatic sheaths, where the particles are  
 accelerated by the local electric field created by the space charge, or in the  
 acceleration region of Hall thrusters. In these regions, the flow may become  
 supersonic [10] invalidating the low Mach regime [1, 2]. This scaling is therefore  
 well-grounded in the core of the plasma where the evolution of the electron may  
 be driven by the following system

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e u_e) = S, \quad (14a)$$

$$\nu_e n_e u_e + \bar{\mathcal{H}}_e (n_e u_e \times B) = -\frac{1}{M_e^2 \kappa_e} (\nabla (n_e T_e) + n_e E), \quad (14b)$$

7 The electronic velocity is provided by a mobility law, where due the magne-  
 8 tization of the plasma, the mobility is not a scalar but a tensor denoted  $\mathbb{M}_{\mathbb{B}}$

$$u_e = -\frac{1}{M_e^2 \kappa_e} \mathbb{M}_{\mathbb{B}} \left( \frac{1}{n_e} \nabla (n_e T_e) + E \right), \quad \mathbb{M}_{\mathbb{B}} = \frac{1}{\nu_e} (\text{ld} + \mathcal{H}_e \mathbb{B})^{-1}, \quad (15a)$$

10 where  $\mathcal{H}_e = \nu_e \bar{\mathcal{H}}_e$ ,  $\text{ld}$  is the identity matrix and  $\mathbb{B}$  the matrix verifying  $\forall v \in \mathbb{R}^3$

$$\mathbb{B}v = v \times b, \quad b = \frac{B}{\|B\|}. \quad (15b)$$

11 Simple algebra provides the following expression of the mobility matrix

$$\begin{aligned} \mathbb{M}_{\mathbb{B}} &= \frac{1}{\nu_e} \frac{1}{1 + \mathcal{H}_e^2} \left( \text{ld} - \mathcal{H}_e \mathbb{B} + \mathcal{H}_e^2 b \otimes b \right), \\ &= \frac{1}{\nu_e} \left( \frac{1}{1 + \mathcal{H}_e^2} \left( (\text{ld} - b \otimes b) - \mathcal{H}_e \mathbb{B} \right) + (b \otimes b) \right) \end{aligned} \quad (15c)$$



1 Note that  $b \otimes b$ , (resp.  $\mathbb{1}d - b \otimes b$ ) is the projector onto the direction aligned with  
2 the magnetic field (resp. onto the directions perpendicular to the magnetic  
3 field). For large values of the magnetic field  $\mathcal{H}_e \gg 1$ , the mobility tensor is  
4 therefore anisotropic. The aligned mobility (with respect to the magnetic field)  
5  $\mu_{\parallel} = \nu_e^{-1}$  ( $\mu_{\parallel} = \mu_e$  in physical units) is large compared to the Pedersen mobility  
6  $\mu_P = \mu_{\parallel}/(1 + \mathcal{H}_e^2) \sim \mu_{\parallel}/\mathcal{H}_e^2$  along the directions perpendicular to the magnetic  
7 field. The third coefficient appearing in the mobility matrix is the Hall mobility  
8  $\mu_H = \mu_{\parallel}\mathcal{H}_e/(1 + \mathcal{H}_e^2) \sim \mu_{\parallel}/\mathcal{H}_e$ . It is also characteristic of the dynamic in the  
9 perpendicular directions, it is indeed at the origin of the so called  $E \times B$  drift.  
10 With these notations, the mobility matrix may be recast into

$$\mathbb{M}_{\mathbb{B}} = \mu_P(\mathbb{1}d - b \otimes b) - \mu_H\mathbb{B} + \mu_{\parallel}(b \otimes b). \quad (16)$$

11 In the drift regime, the electronic density is the solution of a diffusion equa-  
12 tion. It is obtained by inserting the mobility law provided by Eqs. (15) into  
13 Eq. (14a) yielding

$$\frac{\partial n_e}{\partial t} - \frac{1}{M_e^2 \kappa_e} \nabla \cdot (\mathbb{M}_{\mathbb{B}} \nabla (n_e T_e)) = \frac{1}{M_e^2 \kappa_e} \nabla \cdot (\mathbb{M}_{\mathbb{B}} n_e E) + S. \quad (17)$$

14 The electronic system reduces to Eq. (17), the ionic properties being computed  
15 thanks to Eqs. (10). The electric field may be computed thanks to Eqs. (12),  
16 however a more elaborated equation may be derived. In this aim, integrating  
17 Eq. (17) over a (dimensionless) typical time  $\Xi$ , the following estimate can be  
18 proposed

$$n_e(t + \Xi) \approx n_e(t) + \frac{\Xi}{M_e^2 \kappa_e} (\mathbb{M}_{\mathbb{B}} (\nabla (n_e T_e) - n_e \nabla \phi)) + \Xi S, \quad (18)$$

19 providing, thanks to Eqs. (12), the following elliptic equation satisfied by the  
20 electric potential

$$-\nabla \cdot \left( (\lambda^2 + \frac{\Xi}{M_e^2 \kappa_e} n_e \mathbb{M}_{\mathbb{B}}) \nabla \phi \right) = \tilde{n}_i - \tilde{n}_e \quad (19a)$$

21 where

$$\begin{aligned} \tilde{n}_e &= n_e(t) + \frac{\Xi}{M_e^2 \kappa_e} (\mathbb{M}_{\mathbb{B}} \nabla (n_e T_e)) + \Xi S, \\ \tilde{n}_i &= n_i(t) + \Xi \nabla \cdot (n_i u_i) + \Xi S \end{aligned} \quad (19b)$$

22 In Eq. (19), the isotropic contribution stemming from Poisson equation is car-  
23 ried by the squared dimensionless Debye length  $\lambda^2$ . The anisotropy tensor,  
24 proportional the  $(M_e^2 \kappa_e)^{-1}$ , originates from the particle current divergence.

### 25 2.3.3 Quasi-neutral limit

26 The plasma may be assumed quasi-neutral when the Debye length is small com-  
27 pared to the typical length. This regime prevails essentially in regions of large  
28 plasma densities. It amounts to the following limit  $\lambda \rightarrow 0$ . In the quasi-neutral

1 limit, Poisson equation (8) degenerates into the balance of the electronic and  
 2 ionic densities  $n_e = n_i = n$ . Two conclusions may be drawn from this property.  
 3 First, Poisson equation is not well suited for the computation of the electric field  
 4 in the quasi-neutral regime. Second, since the ionic and electronic densities are  
 5 equal, one of the equations (10a) and (14a) is redundant. Classically, Eq. (10a)  
 6 is used to compute the evolution of the plasma density, while the electric field is  
 7 carried out thanks to the continuity equation. This latter equation provides the  
 8 evolution of the charge density  $\rho = n_i - n_e$ , it is an outcome of both Eqs. (10a)  
 9 and (14a), writing

$$\frac{\partial \rho}{\partial t} + \nabla \cdot J = 0, \quad (20)$$

10  $J = n_i u_i - n_e u_e$  being the particle current density. The quasi-neutral limit of  
 11 the continuity equation (20) provides the constraint  $\nabla \cdot J = 0$ . In this regime,  
 12 the electric field is computed to ensure a divergence free current thanks to

$$\nabla \cdot (n u_e) = S - \frac{\partial n}{\partial t} \quad (21)$$

13 where  $n = n_e = n_i$  is the plasma density. The electric field is therefore computed  
 14 thanks to equations governing the evolution of the particles properties rather  
 15 than Maxwell's equations [15], hence the anisotropy of the problem. In the  
 16 combined quasi-neutral and drift approximation limit, the electric field equation  
 17 is indeed derived from Eqs. (19) by letting  $\lambda \rightarrow 0$  yielding

$$-\nabla \cdot \left( \mathbb{M}_{\mathbb{B}} \left( -\nabla(nT_e) + n\nabla\phi \right) \right) = S - \frac{\partial n}{\partial t}. \quad (22)$$

18 In the standard regime, including the inertia of the electrons, the equation  
 19 providing the electric potential is derived from Eqs. (11). We refer, for instance  
 20 to [18] for such a derivation.

### 21 **2.3.4 Field aligned Boltzmann relation**

22 This last asymptotic consists in assuming an infinite anisotropy, letting  $1/\mathcal{H}_e \rightarrow$   
 23 0. The mobility relation defined by Eqs. (15) leads to the following force balance  
 24

$$b \cdot \nabla(nT_e) - nb \cdot \nabla\phi = 0. \quad (23)$$

25 To provide a finite electronic velocity along the magnetic field lines, a zero force  
 26 balance is mandatory along this direction. Note that, owing to the homogeneous  
 27 electronic temperature, this force derives from the potential  $\psi$  defined as

$$\psi = -\phi + T_e \ln \left( \frac{n}{n_0} \right) \quad (24)$$

28  $n_0$  being a reference of the density. Denoting  $\mathcal{F} = \nabla\psi$  the force field, the  
 29 equilibrium stated by Eq. (23) amounts to a zero force regime along the magnetic  
 30 field lines

$$b \cdot \mathcal{F} = 0. \quad (25)$$

1 To outline the characteristics of this regime in a simple framework, the mag-  
 2 netic field is assumed constant and aligned with the  $z$ -coordinate. The force  
 3 balance occurring along the magnetic field lines simplifies into

$$\frac{\partial \phi}{\partial z} = \frac{T_e}{n_e} \frac{\partial n_e}{\partial z}. \quad (26)$$

4 Classically, this differential equation is integrated to provide the so-called Boltz-  
 5 mann relation

$$n_e(x, y, z) = n_0(x, y) \exp\left(\frac{\phi(x, y, z) - \phi_0(x, y)}{T_e(x, y)}\right), \quad (27)$$

6 where  $n_0$ ,  $\phi_0$  and  $T_e$  are independent of the aligned coordinate  $z$ . Combined  
 7 with Poisson equation, it provides a non linear equation satisfied by the electric  
 8 potential

$$-\lambda \Delta \phi = n_i - n_0 \exp\left(\frac{\phi}{T_e}\right). \quad (28)$$

9 Note that this non linear equation is not degenerate in the quasi-neutral limit  
 10 [18]. In the context of quasi-neutral plasma modelling, Eq. (27) is used to  
 11 compute the electric potential thanks to the density with

$$\phi(x, y, z) = \phi_0(x, y) + T_e(x, y) \ln\left(\frac{n(x, y, z)}{n_0(x, y)}\right), \quad (29)$$

12 In the literature [23, 38], this identity is sometimes referred to as the Morozov  
 13 approximation [34]. This equation is coupled with the ionic system (10) to close  
 14 the system providing the evolution of the plasma density.

## 15 **3 Numerical methods for quasi-neutral fluid mod-** 16 **els of magnetically confined low temperature** 17 **plasmas.**

### 18 **3.1 Model and geometrical configuration**

The purpose here is to state the complete set of equations operated to illus-  
 trate the difficulty raised by quasi-neutral modelling of plasma thrusters. The  
 computations are restricted to two dimensional configurations, in a plane con-  
 taining both the electric and the magnetic field. The system defining the model  
 is specified in dimensional units. Let  $n$  be the plasma density,  $v$  the ionic mean  
 velocity and  $\Gamma_e$  the electronic density flux, these equations write

$$\frac{\partial n}{\partial t} + \nabla \cdot (nv) = S, \quad \text{in } (0, \infty) \times \Omega, \quad (30a)$$

$$\frac{\partial}{\partial t}(nv) + \nabla \cdot (nv \otimes v) = \frac{e}{m_i} nE, \quad \text{in } (0, \infty) \times \Omega, \quad (30b)$$

$$\nabla \cdot \Gamma_e = S - \frac{\partial n}{\partial t} \quad \text{in } \Omega, \quad (30c)$$

1 with

$$\Gamma_e = \mu_e(n\nabla_{\parallel}\phi - \nabla_{\parallel}(nk_B T_e)) + \mu_e\varepsilon(n\nabla_{\perp}\phi - \nabla_{\perp}(nk_B T_e)), \quad (30d)$$

2 the electrostatic field and potential satisfying the following identity  $E = -\nabla\phi$ .  
 3 Note that, owing to the geometrical configuration, the Hall components in the  
 4 mobility law defined by Eq. (16) are dropped out of these equations, hence  
 5 the definition of the electronic density flux as a function of the only parallel  
 6 mobility  $\mu_{\parallel} = \mu_e = em_e/\nu_e$ ,  $\nu_e$  being the collision frequency against neutral,  
 7 and the Perderson mobility  $\mu_P = \mu_e\varepsilon$ . The anisotropic parameter  $\varepsilon$  is related  
 8 to the electronic Hall parameter  $\mathcal{H}_e$  thanks to

$$\varepsilon = \frac{1}{1 + \mathcal{H}_e^2}, \quad \mathcal{H}_e = \mu_e\|B\| = \frac{\omega_{c,e}}{\nu_e}. \quad (30e)$$

9 The source term in Eq. (30a) accounts for the ionization. The following  
 10 expression will be considered in Sec. 4.2

$$S(x, y) = \nu n_0 \exp(-(\tau y)^2), \quad (30f)$$

11 where  $\nu$  is the ionization frequency  $n_0$  the typical plasma density and  $\tau > 0$   
 12 parametrizes the distribution of the neutral density in the domain. The parallel  
 13 and perpendicular gradients are defined for any smooth function  $\psi$  as

$$\nabla_{\parallel}\psi = b \otimes b \nabla\psi, \quad \nabla_{\perp}\psi = (\text{Id} - b \otimes b)\nabla\psi, \quad b = \frac{B}{\|B\|}. \quad (30g)$$

The computational domain, denoted  $\Omega \times [0, T]$ , consists of  $\Omega = [0, L_x] \times$   
 $[-L_y/2, L_y/2]$  where  $L_x$  and  $L_y$  are positive real numbers. The domain boundary  
 is split into two parts  $\partial\Omega_x = [0, L_x] \times \{-L_y/2, L_y/2\}$  and  $\partial\Omega_y = \{0, L_x\} \times$   
 $[-L_y/2, L_y/2]$ , the following boundary conditions supplementing the system (30)

$$\nabla n \cdot \mathbf{n} = 0 \quad \text{on } (0, T) \times \partial\Omega_y, \quad (31a)$$

$$\nabla(nv)\mathbf{n} \cdot \mathbf{n} = 0 \quad \text{on } (0, T) \times \partial\Omega_x, \quad (31b)$$

$$v \cdot \mathbf{n} = 0 \quad \text{on } (0, T) \times \partial\Omega_y, \quad (31c)$$

$$v \cdot \mathbf{n} = v_B \quad \text{on } (0, T) \times \partial\Omega_x, \quad (31d)$$

$$\Gamma_e \cdot \mathbf{n} = 0 \quad \text{on } \partial\Omega_y, \quad (31e)$$

$$\Gamma_e \cdot \mathbf{n} = \Gamma_{\beta}(\phi) \quad \text{on } \partial\Omega_x. \quad (31f)$$

14 The domain outward normal is denoted  $\mathbf{n}$ ,  $v_B$  is the Bohm velocity

$$v_B^2 = \frac{k_B T_e}{m_i}. \quad (31g)$$

15 Specifying the boundary condition of the quasi-neutral model to account the  
 16 physics that develops on the sheath edge is an intricate issue. We propose and  
 17 investigate here the following path. On the one hand, the electrons are assumed  
 18 to flow outside the domain along the magnetic field lines with the most probable

1 velocity computed from the local Maxwellian distribution ( $\sqrt{k_B T_e / 2\pi m_e}$ ). On  
 2 the other hand, when the magnetic field is parallel to the boundary, the electron  
 3 flux is assumed to match that of the ions. Denoting  $\beta$  the angle measured  
 4 between the magnetic field and  $\mathbf{n}$  the outward normal on  $\partial\Omega_x$ , the following  
 5 boundary condition is therefore considered

$$\Gamma_\beta(\phi) = n \sqrt{\frac{k_B T_e}{2\pi m_e} \cos^2(\beta) + v_B^2 \sin^2(\beta)} \exp\left(-\frac{e\phi}{k_B T_e}\right). \quad (31h)$$

6 The initial condition is prescribed thanks to

$$n(t=0) = n_0, \quad v(t=0) = v_0, \quad \text{on } \Omega. \quad (32)$$

In this model, the electric potential is used to enforce the quasi-neutrality constraint (30c). It yields the following non-linear anisotropic problem for  $\phi$

$$-\nabla \cdot (\mu n \nabla_{\parallel} \psi + \mu n \varepsilon \nabla_{\perp} \psi) = S - \frac{\partial n}{\partial t} \quad \text{in } \Omega, \quad (33a)$$

$$(\mu n \nabla_{\parallel} \psi + \mu n \varepsilon \nabla_{\perp} \psi) \cdot \mathbf{n} = 0 \quad \text{on } \partial\Omega_y, \quad (33b)$$

$$(\mu n \nabla_{\parallel} \psi + \mu n \varepsilon \nabla_{\perp} \psi) \cdot \mathbf{n} = \Gamma_\beta \left( -\psi + \frac{k_B T_e}{e} \ln \left( \frac{n}{n_0} \right) \right) \quad \text{on } \partial\Omega_x, \quad (33c)$$

7 where

$$\psi = -\phi + \frac{k_B T_e}{e} \ln \left( \frac{n}{n_0} \right). \quad (33d)$$

The non linearity of the problem stems from the boundary condition (33c). This problem is approximated by a sequence of linearised problems providing the solution estimates  $(\psi^{(k)})_{k \geq 0}$  thanks to

$$-\nabla \cdot (\mu n \nabla_{\parallel} \psi^{(k+1)} + \mu n \varepsilon \nabla_{\perp} \psi^{(k+1)}) = S - \frac{\partial n}{\partial t} \quad \text{in } \Omega, \quad (34a)$$

$$(\mu n \nabla_{\parallel} \psi^{(k+1)} + \mu n \varepsilon \nabla_{\perp} \psi^{(k+1)}) \cdot \mathbf{n} = 0 \quad \text{on } \partial\Omega_y, \quad (34b)$$

$$\begin{aligned} & (\mu n \nabla_{\parallel} \psi^{(k+1)} + \mu n \varepsilon \nabla_{\perp} \psi^{(k+1)}) \cdot \mathbf{n} = \\ & - \Gamma'_\beta \left( -\psi^{(k)} + \frac{k_B T_e}{e} \ln \left( \frac{n}{n_0} \right) \right) (\psi^{(k+1)} - \psi^{(k)}) \quad \text{on } \partial\Omega_x, \end{aligned} \quad (34c)$$

8 where  $\Gamma'_\beta$  is the derivative of  $\Gamma_\beta$ , obeying the relationship

$$\Gamma'_\beta(\varphi) = -\frac{e}{k_B T_e} \Gamma_\beta(\varphi). \quad (34d)$$

### 9 3.2 Handling numerically the anisotropy

The difficulty raised by the anisotropic nature of the problem is analyzed in this section. To support these investigations, the system (34) is simplified, assuming

$\mu n = 1$  and  $\Gamma'_\beta \equiv 0$ , yielding the following toy problem

$$-\Delta_\perp \psi - \frac{1}{\varepsilon} \Delta_\parallel \psi = f, \quad \text{in } \Omega \quad (35a)$$

$$(\varepsilon \nabla_\perp \psi + \nabla_\parallel \psi) \cdot \mathbf{n} = 0, \quad \text{on } \partial\Omega_N, \quad (35b)$$

$$\psi = 0 \quad \text{on } \partial\Omega_D \quad (35c)$$

with

$$\partial\Omega_N = \{\mathbf{x} \in \partial\Omega, b(\mathbf{x}) \cdot \mathbf{n}(\mathbf{x}) \neq 0\}, \quad \partial\Omega_D = \partial\Omega \setminus \partial\Omega_N, \quad (35d)$$

$$\Delta_\parallel \psi = \nabla \cdot \nabla_\parallel \psi, \quad \Delta_\perp \psi = \nabla \cdot \nabla_\perp \psi. \quad (35e)$$

Let,  $p$  be the precision order on the numerical schemes at hand to carry out the approximation of the differential operators (with respect to the coordinates), the following estimates hold true:

$$(\Delta_\parallel^h \Psi^h)_{i,j} = \Delta_\parallel \psi(x_i, y_j) + \mathcal{O}_\parallel(h^p), \quad (\Delta_\perp^h \Psi^h)_{i,j} = \Delta_\perp \psi(x_i, y_j) + \mathcal{O}_\perp(h^p).$$

- 1 The discrete operators are denoted  $\Delta_\parallel^h$  and  $\Delta_\perp^h$ ,  $\Psi^h$  is the discrete approximation  
 2 of the solution, the mesh being defined by the node positions  $(x_i, y_j)$  and the  
 3 typical mesh size  $h$ . The truncation errors  $\mathcal{O}_\parallel(h^p)$  and  $\mathcal{O}_\perp(h^p)$  are functions of  
 4 the mesh size and the derivatives of the solution and magnetic field with respect  
 5 to  $x$  and  $y$ . This yields the following scheme:

$$-(\Delta_\perp^h \Psi^h)_{i,j} - \frac{1}{\varepsilon} (\Delta_\parallel^h \Psi^h)_{i,j} = f_{i,j}^h - \mathcal{O}_\perp(h^p) - \frac{1}{\varepsilon} \mathcal{O}_\parallel(h^p) \quad (36)$$

- 6 This unravels an amplification of the truncation error  $\mathcal{O}_\parallel(h^p)$  issued from par-  
 7 allel operator discretization by  $1/\varepsilon$ . A deterioration of the numerical method  
 8 precision with decreasing  $\varepsilon$ -values can therefore be anticipated, precisely a linear  
 9 growth of the error with  $\varepsilon^{-1}$ , eventually leading to ineffective computations for  
 10 large anisotropies. We refer to Sec. 4.1 for numerical investigations illustrating  
 11 this feature and to [41] for a thorough analysis of this issue.

A workaround consists in working a "rescaled" variable harnessed to cancel this amplification of the truncation error, owing to the property  $\nabla_\parallel q = \varepsilon^{-1} \nabla_\parallel \psi$ . The re-scaled variable may be computed thanks to  $\psi$  by substituting  $\varepsilon^{-1} \nabla_\parallel \psi$  by  $\nabla_\parallel q$  in Eqs. (35). This provides

$$\begin{aligned} -\Delta_\parallel q &= f + \Delta_\perp \psi, & \text{in } \Omega \\ \nabla_\parallel q \cdot \mathbf{n} &= -\nabla_\perp \psi \cdot \mathbf{n}, & \text{on } \partial\Omega_N, \end{aligned}$$

This system is not well posed for  $q$ , since the solution of this problem can be augmented by any function with no parallel gradient. Uniqueness may be restored in this system by imposing the value of  $q$  on every field line. Let  $\partial\Omega_0$  be the subset of  $\Omega$  onto which the condition  $q = 0$  is imposed to restore the well posedness of the problem. The definition of  $\partial\Omega_0$  is specific to the magnetic field geometry and will be specified in the sequel. This condition is introduced

into the system by means of a Lagrange multiplier. This yields the following set of equations to compute the re-scaled variable  $q$  together with the Lagrange multiplier  $\mathcal{L}$  defined on  $\partial\Omega_0$  ( $\mathcal{L} \equiv 0$  on  $\Omega/\partial\Omega_0$ )

$$-\Delta_{\parallel}q + \mathcal{L} = f + \Delta_{\perp}\psi \quad \text{in } \Omega \quad (38a)$$

$$\nabla_{\parallel}q \cdot \mathbf{n} = -\nabla_{\perp}\psi \cdot \mathbf{n} \quad \text{on } \partial\Omega_N, \quad (38b)$$

$$q = 0 \quad \text{on } \partial\Omega_0 \quad (38c)$$

This problem is coupled with

$$-\Delta_{\parallel}\psi = -\varepsilon\Delta_{\parallel}q \quad \text{in } \Omega \quad (38d)$$

$$\nabla_{\parallel}\psi \cdot \mathbf{n} = -\varepsilon\nabla_{\parallel}q \cdot \mathbf{n} \quad \text{on } \partial\Omega_N, \quad (38e)$$

$$\psi = 0 \quad \text{on } \partial\Omega_D, \quad (38f)$$

- 1 to define a set of equations providing  $(\psi, q, \mathcal{L})$  and referred to as the augmented  
2 Micro-Macro system. The merits of the re-scaled system defined by Eqs. (38)  
3 are outlined thanks to a discretization of Eq. (38d)

$$-\left(\Delta_{\parallel}^h\Psi^h\right)_{i,j} = -\varepsilon\left(\Delta_{\parallel}^hQ^h\right)_{i,j} + \mathcal{O}_{\parallel,\psi}(h^p) + \varepsilon\mathcal{O}_{\parallel,q}(h^p), \quad (39)$$

- 4 In this equation  $Q^h$  is the numerical approximation of  $q$ ,  $\mathcal{O}_{\parallel,\psi}(h^p)$  and  $\mathcal{O}_{\parallel,q}(h^p)$   
5 are the truncation errors stemming from the discretization of  $\Delta_{\parallel}\psi$  and  $\Delta_{\parallel}q$ .  
6 For intense anisotropies, the contribution of  $Q^h$  in this equation is masked by  
7 the truncation error:  $\varepsilon\mathcal{O}_{\parallel,q}(h^p) \ll \mathcal{O}_{\parallel,\psi}(h^p)$ . Eq. (39) accounts for the property  
8  $-\Delta\psi = 0$ , satisfied by the solution in the limit  $\varepsilon \rightarrow 0$ , but with the precision of  
9 the numerical scheme  $\mathcal{O}(h^p)$ . Finally, note that Eqs. (38a-38c) are independent  
10 of the anisotropy, therefore any discretization provides a numerical method free  
11 from an error amplification when  $\varepsilon \rightarrow 0$ .

The augmented Micro-Macro method will be compared to the classical "In-flow" method which consists of the following set of equations

$$-\Delta_{\perp}\psi - \Delta_{\parallel}q = f \quad \text{in } \Omega \quad (40a)$$

$$-\Delta_{\parallel}\psi = -\varepsilon\Delta_{\parallel}q \quad \text{in } \Omega \quad (40b)$$

$$\nabla_{\parallel}q \cdot \mathbf{n} = -\nabla_{\perp}\psi \cdot \mathbf{n} \quad \text{on } \partial\Omega_N \setminus \partial\Omega_0, \quad (40c)$$

$$\nabla_{\parallel}\psi \cdot \mathbf{n} = -\varepsilon\nabla_{\parallel}q \cdot \mathbf{n} \quad \text{on } \partial\Omega_N, \quad (40d)$$

$$\psi = 0 \quad \text{on } \partial\Omega_D, \quad (40e)$$

$$q = 0 \quad \text{on } \partial\Omega_0 \quad (40f)$$

- 12 where  $\partial\Omega_0$  is a subset of  $\partial\Omega_N$  with

$$\partial\Omega_0 = \{\mathbf{x} \in \partial\Omega_N, b(\mathbf{x}) \cdot \mathbf{n}(\mathbf{x}) > 0\}. \quad (40g)$$

- 13 In the Inflow MM method, the boundary condition for  $q$  on one part of  $\partial\Omega_N$  is  
14 substituted by a zero condition yielding to Eqs. (40c) and (40f). No Lagrange  
15 multiplier is therefore used to impose the value of  $q$  on every field line in this  
16 method.

A similar augmented Micro-Macro (a-MM) system is stated for the linearised problem (34), yielding

$$-\nabla \cdot \left( \mu n \varepsilon \nabla_{\parallel} q^{(k+1)} + \mu n \varepsilon \nabla_{\perp} \psi^{(k+1)} \right) + \mathcal{L}^{(k+1)} = S - \frac{\partial n}{\partial t} \quad \text{in } \Omega, \quad (41a)$$

$$-\nabla \cdot \left( \mu n \varepsilon \nabla_{\parallel} q^{(k+1)} - \mu n \nabla_{\parallel} \psi^{(k+1)} \right) = 0 \quad \text{in } \Omega, \quad (41b)$$

$$\left( \mu n \varepsilon \nabla_{\parallel} q^{(k+1)} + \mu n \varepsilon \nabla_{\perp} \psi^{(k+1)} \right) \cdot \mathbf{n} = 0 \quad \text{on } \partial\Omega_y, \quad (41c)$$

$$q^{(k+1)} = 0 \quad \text{on } \partial\Omega_y, \quad (41d)$$

$$\left( \mu n \varepsilon \nabla_{\parallel} q^{(k+1)} + \mu n \varepsilon \nabla_{\perp} \psi^{(k+1)} \right) \cdot \mathbf{n} = \quad \text{on } \partial\Omega_x, \quad (41e)$$

$$-\Gamma'_{\beta} \left( -\psi^{(k+1)} + \frac{k_B T_e}{e} \ln \left( \frac{n}{n_0} \right) \right) \left( \psi^{(k+1)} - \psi^{(k)} \right)$$

$$\left( \mu n \varepsilon \nabla_{\parallel} q^{(k+1)} - \mu n \nabla_{\parallel} \psi^{(k+1)} \right) \cdot \mathbf{n} = 0 \quad \text{on } \partial\Omega_x, \quad (41f)$$

$$q^{(k+1)} = 0 \quad \text{on } \partial\Omega_0 \quad (41g)$$

## 1 4 Demonstrative calculations

### 2 4.1 Validation of the augmented Micro-Macro method

3 In this section, the capability of the elliptic problem solver to recover a precise  
4 approximation of the force field and potential ( $\mathcal{F}$  and  $\psi$ ), irrespective to the  
5 anisotropy strength, is examined. In this aim, a manufactured solution of the  
6 toy model defined by Eqs. (35) is therefore proposed. This simplified set-up  
7 enables to carry out analytically the computations, providing an exact reference  
8 solution to validate the numerical methods mobilized for the resolution of the  
9 anisotropic problem. The computational domain is  $\Omega = [0, 1]^2$ , the magnetic  
10 field is provided by the following equations

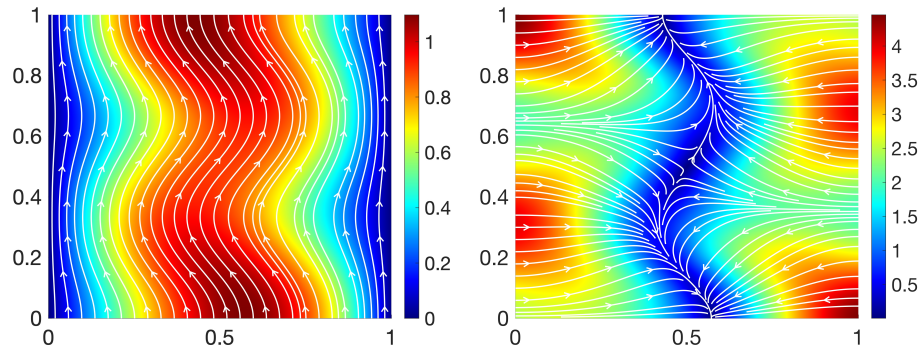
$$B_x(x, y) = \pi \aleph \zeta (x^2 - x) \sin(\aleph \pi y), \quad B_y(x, y) = \zeta (2x - 1) \cos(\aleph \pi y) + \pi. \quad (42a)$$

11 The manufactured solution for the potential, denoted  $\psi_m$ , is defined by means  
12 of two components  $\psi_0$  and  $\psi_1$  with

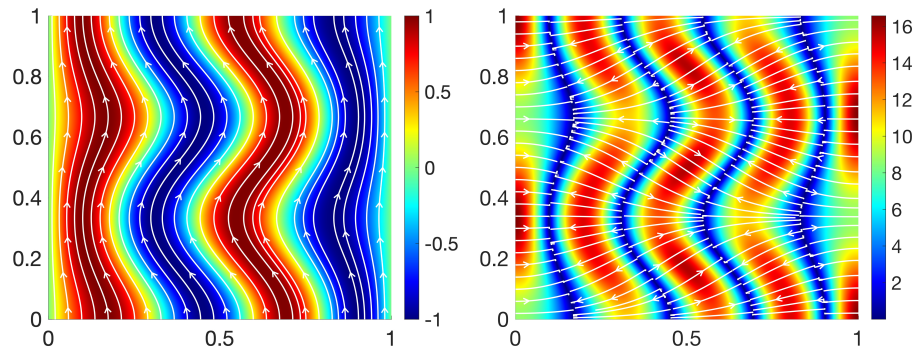
$$\begin{aligned} \psi_m(x, y) &= \psi_0(x, y) + \varepsilon \psi_1(x, y), \\ &= \sin \left( k(\pi x + \zeta(x^2 - x) \cos(\aleph \pi y)) \right) + \varepsilon \left( \cos(2\pi y) \sin(\pi x) \right). \end{aligned} \quad (42b)$$

13 The curvature of the magnetic field is parametrized by  $\zeta \in \mathbb{R}$ ,  $\zeta \geq 0$ . The  
14 second parameter,  $k \in \mathbb{N}$ , provides a control of the perpendicular gradient of  
15 the solution in the limit  $\varepsilon \rightarrow 0$ , the variations of the solution perpendicular to  
16 the magnetic field being reduced to that of  $\psi_0$  for large anisotropy strengths.  
17 The set-up associated to the manufactured solution is illustrated on the plots  
18 of Fig. 2. The auxiliary variable is set to zero along an horizontal line inter-  
19 secting any field line, at the bottom ( $y = 0$  or the top  $y = 1$ ) of the compu-  
20 tational domain. This amounts to the definition  $\partial\Omega_0 = \{(x, y) \in ]0, 1[ \times \{0\}\}$ .

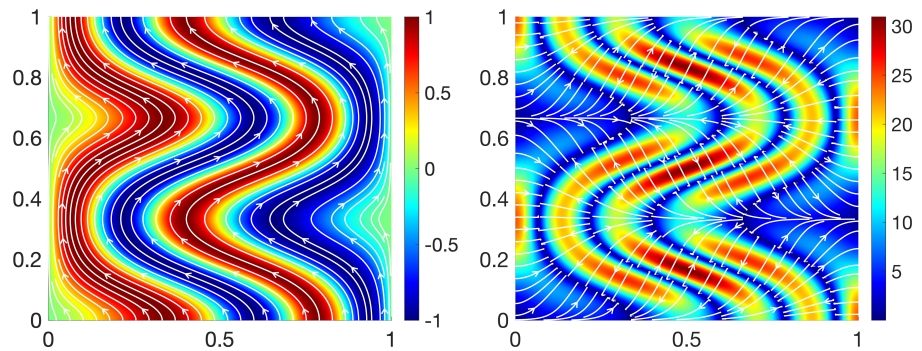




(a)  $\zeta = 1, k = 1, \varepsilon = 10^{-1}$ .



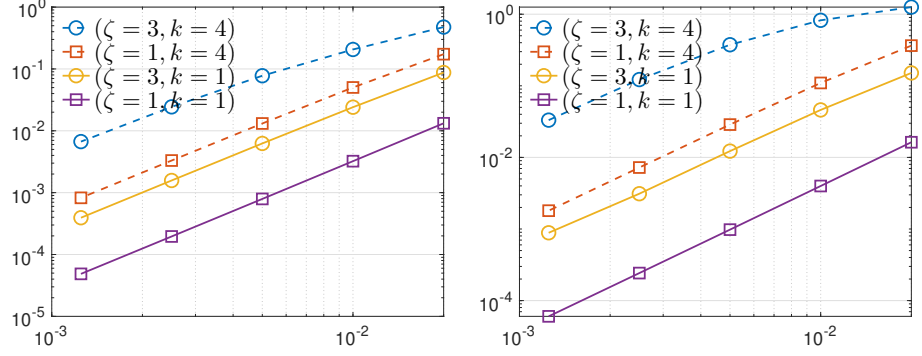
(b)  $\zeta = 1, k = 4, \varepsilon = 10^{-6}$ .



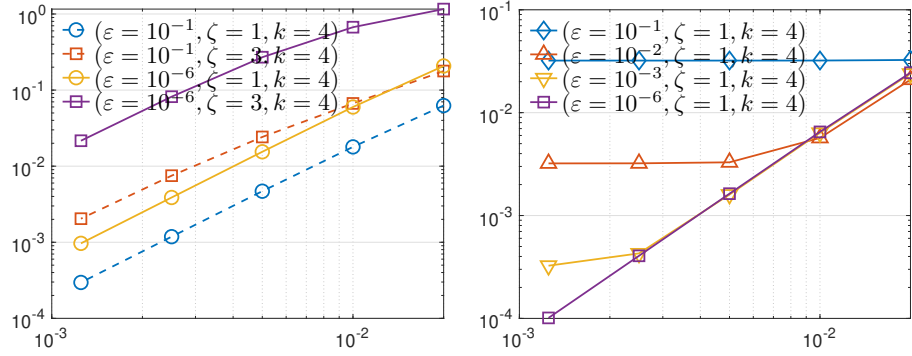
(c)  $\zeta = 3, k = 4, \varepsilon = 10^{-6}$ .

Figure 2: Manufactured solution defined by Eqs. (42): Magnetic field lines and potential values ( $\psi$ ) in a color scale (left); force field ( $\mathcal{F}$ ) lines and magnitude  $\|\mathcal{F}\|_2$  in a color scale (right) for  $\aleph = 3$ .

1 The precision of the numerical method is not experienced to depend significantly on the choice of  $\partial\Omega_0$ . The plots of Fig. 3a and 3b are related to the

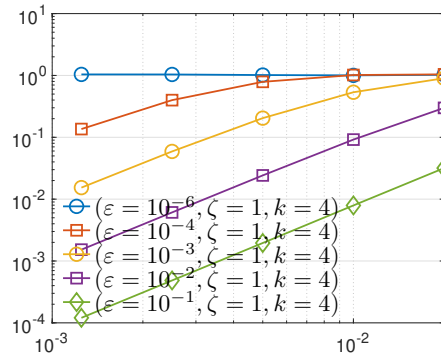


(a) (a-MM):  $\|\Psi^h - \psi_m\|_\infty / \|\psi_m\|_\infty$ ,  $\varepsilon = 10^{-1}$ . (b) (a-MM):  $\|\Psi^h - \psi_m\|_\infty / \|\psi_m\|_\infty$ ,  $\varepsilon \leq 10^{-6}$ .



(c) (a-MM):  $\|\mathcal{F}^h - \mathcal{F}_m\|_2 / \|\mathcal{F}_m\|_2$ .

(d) (a-MM):  $\|b \cdot \mathcal{F}^h\|_2 / \|\mathcal{F}_m\|_2$ .



(e) (FD):  $\|\Psi^h - \psi_m\|_\infty / \|\psi_m\|_\infty$ .

Figure 3: Manufactured solution: Relative error norms for the potential  $\Psi^h$  and force field  $\mathcal{F}^h$  carried out by either a finite difference (FD) or the augmented Micro-Macro (a-MM) scheme as functions of the mesh size ( $\aleph = 3$ ).

2  
3 accuracy of  $\Psi^h$  the potential numerical approximation. The precision of the  
4 augmented Micro-Macro method (a-MM) is observed to be effective and hardly  
5 altered by  $\varepsilon$ -values. The same conclusions may be drawn from the approxima-

1 tion of the force field  $\mathcal{F} = \nabla\psi$  plotted on Fig. 3c. Finally, the property to  
 2 recover the orthogonality of the magnetic and force fields is investigated thanks  
 3 to Fig. 3d. The deviation from the orthogonality is proportional to  $\varepsilon$  (precisely  
 4  $\varepsilon b \cdot \nabla\psi_1 = b \cdot \nabla\psi_m$ ). This is what the numerical approximation reproduces as  
 5 long as the precision of the discretization is sufficient. Indeed, the plots of Fig. 3c  
 6 confirm the estimate  $\|\mathcal{F}^h - \nabla\psi_m\|_2 = \mathcal{O}(h^p)$ ,  $h$  denoting the typical mesh size  
 7 and  $p$  the approximation order ( $p = 2$  for these computations). It follows that  
 8  $\|b \cdot \mathcal{F}^h\|_2 = \mathcal{O}(\varepsilon) + \mathcal{O}(h^p)$ . This estimate is in line with the plateau observed  
 9 on the plots of Fig. 3d related to computations carried out with refined meshes  
 10 and moderate anisotropy strengths ( $\varepsilon \geq 10^{-3}$ ). These plateaus account for  
 11 an orthogonality default dominating the approximation error ( $\mathcal{O}(\varepsilon) \geq \mathcal{O}(h^p)$ ).  
 12 Conversely, for  $\varepsilon < 10^{-4}$ , the numerical method is not precise enough, the  
 13 deviation from the orthogonality is hidden by the discretization error.

14 The picture is very different for approximations computed thanks to a dis-  
 15 cretization of the anisotropic problem using finite differences (FD), as displayed  
 16 on Fig. 3e. The amplification of the truncation error by  $\varepsilon^{-1}$  is clearly illustrated  
 17 on these error plots: the same convergence rate is observed for  $\varepsilon = 10^{-1}$  and  
 18  $\varepsilon = 10^{-2}$  (eventually for  $\varepsilon = 10^{-3} - 10^{-4}$  and refined meshes), however, the er-  
 19 ror value is increased by one order of magnitude when  $\varepsilon$  is decreased by 10. The  
 20 precision of this method obeys the following estimate  $\|\Psi^h - \psi_m\|_2 = \mathcal{O}(h^p \cdot \varepsilon^{-1})$ ,  
 21 in line with Eq. (36). This prevents the computation of an effective numerical  
 22 approximation for intense anisotropy.

## 23 4.2 Plasma confinement in a cusp-shaped magnetic field

### 24 4.2.1 Assessment of the numerical model to reproduce the physics 25 of plasma thruster

The purpose here is to provide representative simulations of the physics involved  
 in plasma thruster operating. Simulating the whole device is far beyond the  
 scope of the present work, the model at hand is too coarse for such an ambitious  
 goal. However, we aim to produce meaningful simulations of plasma confinement  
 and prove that the numerical method developed within this paper is efficient to  
 carry out simulations with parameters (anisotropies) representative of plasma  
 thrusters. Specifically, the plasma confinement by a cusp-shaped magnetic field  
 [37, 25] is investigated. This is quite challenging for numerical methods. In  
 part due to the singularity of the magnetic field, or more precisely that of the  
 normalized magnetic field, the magnetic field vanishing locally (in space). More  
 importantly, due to the significant curvature of the magnetic field lines. Finally,  
 this is also due to the concentration of magnetic field lines in punctual regions of  
 the simulation domain. The specific application targeted here is indeed related

to a cusp shaped magnetic field [31]  $B = (B_x, B_y)$  defined as

$$B_x(x, y) = -\sqrt{\gamma} \sin\left(\frac{2\pi x}{L_x}\right) \left( \exp(-\pi y_-) - \exp(-\pi y_+) \right), \quad (43a)$$

$$B_y(x, y) = \sqrt{\gamma} \cos\left(\frac{2\pi x}{L_x}\right) \left( \exp(-\pi y_-) + \exp(-\pi y_+) \right), \quad (43b)$$

$$y_- = \frac{L_y - 2y}{L_y}, \quad y_+ = \frac{L_y + 2y}{L_y} \quad (43c)$$

1 and plotted on Fig. 4a. The magnitude of the magnetic field is parameter-  
 2 ized by  $\gamma > 0$ . The model defined by Eqs. (30-33) is discretized thanks to  
 3 the methods detailed in Appendix A. Note that these discretizations are quite  
 4 standard, the difficulty being addressed algebraically, thanks to the introduc-  
 5 tion of the re-scaled variable into the linearized system (41). The numerical  
 6 investigations are performed on a square domain with  $L_x = L_y = 0.1$  m.  
 7 A plasma of Argon is considered, with a typical density  $n_0 = 10^{18} \text{ m}^{-3}$  and  
 8 an ionic mass  $m_i = 6.69 \cdot 10^{-26} \text{ kg}$ , the electronic temperature and mobility  
 9 being set to  $T_e = 11604 \text{ K}$  (1 eV),  $\mu_e = 10^4 \text{ T}^{-1}$ . The magnetic field am-  
 10 plitude is  $B_0 = 10^{-1} \text{ T}$  yielding a typical Hall parameter  $\mathcal{H}_e = 10^3$ , at the  
 11 plasma edge, this value being much weaker in the center. The initial data con-  
 12 sists of  $n(x, y, t = 0) = n_0 = 10^{18} \text{ m}^{-3}$ ,  $v(x, y, t = 0) = 2v_B y / L_y \text{ m} \cdot \text{s}^{-1}$ ,  
 13  $v_B = \sqrt{k_B T_e / m_i} = 1.55 \cdot 10^3 \text{ m} \cdot \text{s}^{-1}$  being the Bohm velocity. Note that, with  
 14 this value of the Hall parameter, the ratio between the parallel and the perpen-  
 15 dicular mobilities, is as large as  $10^6$  near the vessel walls, as depicted on the plot  
 16 of Fig. 4b. The plasma creation in the inter-electrode chamber is accounted for  
 17 by the source term in Eq. (30f) with  $\nu = 1.55 \cdot 10^3 \text{ s}^{-1}$  and  $\tau = 1.3 \cdot 10^2 \text{ m}^{-1}$ . The  
 18 ionization is predominant in the centre of the inter electrode region as illustrated  
 on Fig. 4c.

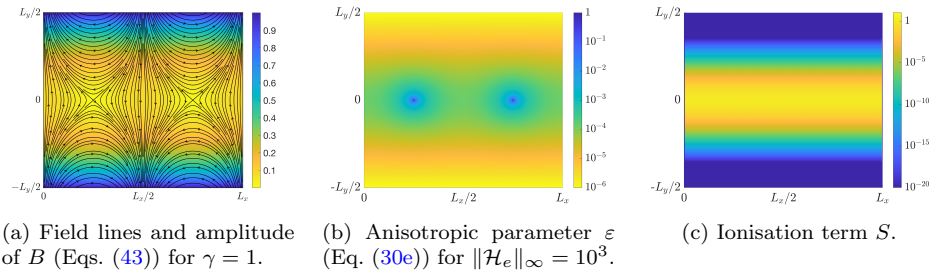


Figure 4: Set-up for plasma confinement by a cusp-shaped magnetic field.

19  
 20 The purpose here, is to capture the steady state of the system. The plasma  
 21 characteristics remain unchanged when the loss of particles along the electrodes  
 22 is matched by the ionisation in the inter-electrodes region. The computations  
 23 are carried out on a mesh with  $399 \times 399$  nodes to avoid the singularity of the

1 magnetic field in  $\{L_x/4, 3L_x/4\} \times \{0\}$ . The steady state defines a regime very  
 2 similar to the one investigated in the previous section: in the regions of large  
 3 anisotropies (near the electrodes), the source term in Eq. (33a) is vanishing,  
 4 therefore, the solution may develop parallel and perpendicular gradients with  
 5 very disparate magnitudes. This is confirmed by the plot of  $\psi$  the solution of  
 the anisotropic problem as displayed on Fig. 5. This variable is almost constant

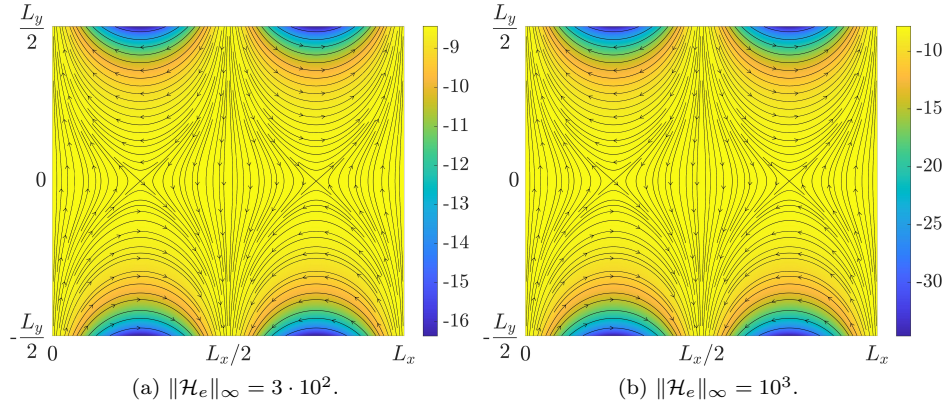


Figure 5: Solution of the anisotropic problem  $\psi$  ( $\text{V} \cdot \text{m}^{-1}$ ) in a color scale and magnetic field lines carried out with different intensities of magnetic field.

6 along the magnetic field lines near the electrodes while the variations perpendicular  
 7 to the magnetic field are large. The confinement of the plasma is manifest  
 8 on the plot of the density obtained at the steady state (see Fig. 6). For small  
 9 magnetization intensity ( $\|\mathcal{H}_e\|_\infty = 10$ , see Fig. 6a) the density created in the  
 10 middle of the inter-electrode region is almost uniformly transported towards the  
 11 electrodes as depicted by the plot of Fig 7a. With the increase of the magnetic  
 12 field intensity, quasi-vacuum basins are formed along the electrodes, centred at  
 13  $x = \{L_x/4, 3L_x/4\}$  in between the cusps of the magnetic field, as depicted on the  
 14 plots of Figs. 6b–6d. The regions that are not connected to the middle of the  
 15 inter-electrode chamber by the magnetic field lines, where the ionization is the  
 16 most effective, are drained from particles. The inflow of particles from the center  
 17 of the chamber, where the ionization is the most effective, into these basins  
 18 is attenuated by the magnetization: the density decreases below  $10^6 \text{ m}^{-3}$  for  
 19  $\mathcal{H}_e = 10^3$  while it remains larger to  $10^{12} \text{ m}^{-3}$  for  $\mathcal{H}_e = 3 \cdot 10^2$ . This is explained  
 20 by the mitigation of the transport perpendicular to the magnetic field with the  
 21 increase of the field intensity. The plots of the electronic flux (Fig. 7) show that  
 22 the electrons are deflected in regions where the magnetic field lines are converg-  
 23 ing. The ions are accelerated by the electric field (see Fig. 8) towards the same  
 24 regions as displayed by the plots of Fig. 9.

26 The confinement of the plasma may be assessed by the space integral of the  
 27 particle number density over the computational domain at the steady state.  
 28 This quantity is plotted on Fig. 10. Note that these computations are carried



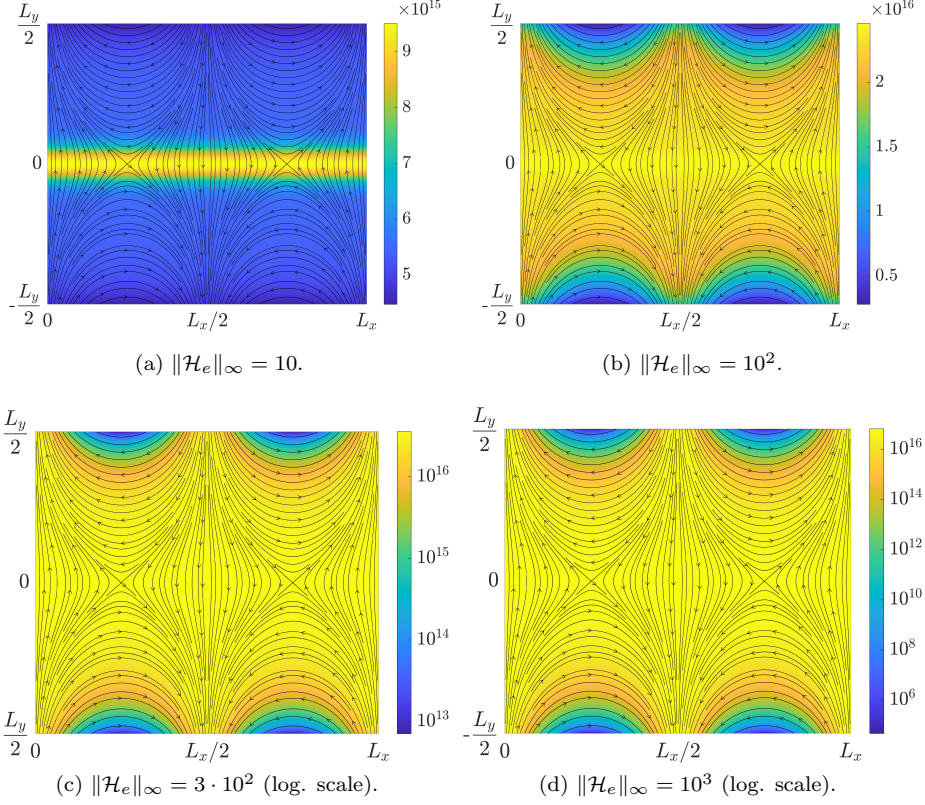


Figure 6: Plasma density (in a logarithmic color scale for subplots (c) and (d)) and magnetic field lines carried out with different intensities of magnetic field.

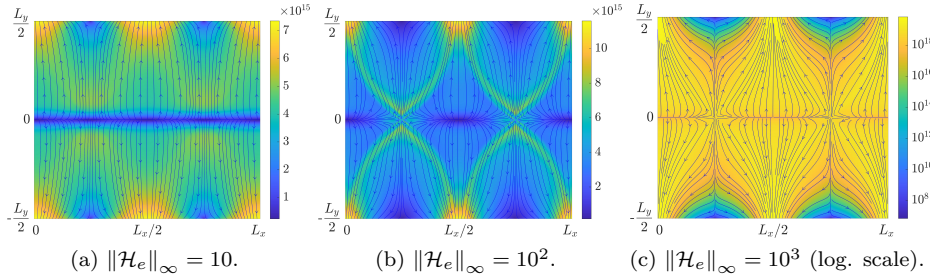


Figure 7: Electronic flux density  $\Gamma_e = nu_e$  ( $m^{-2} \cdot s^{-1}$ ) for different magnetisation intensities.

- 1 out with the same source term but different values of the Hall parameter. The
- 2 total number of particles is observed to increase with the Hall parameter which

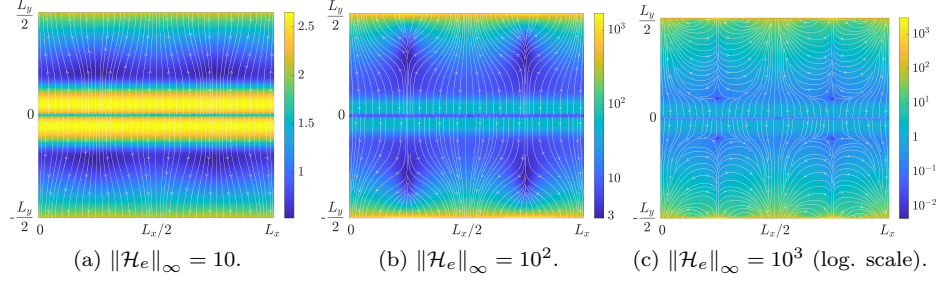


Figure 8: Electric field magnitude ( $\text{V} \cdot \text{m}^{-1}$ ) in a color scale and associated field lines for different magnetisation intensities.

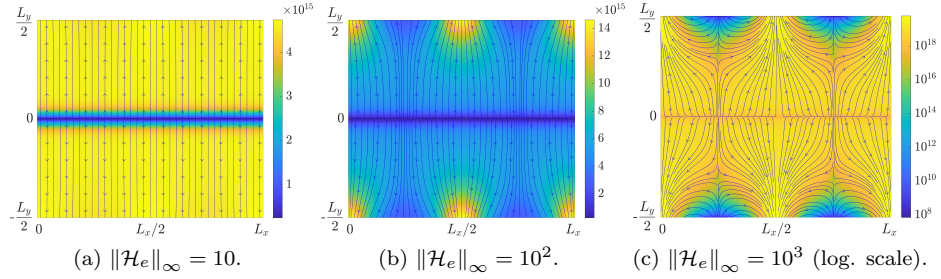


Figure 9: Ionic flux density  $\Gamma_i = nu_i$  ( $\text{m}^{-2} \cdot \text{s}^{-1}$ ) for different magnetisation intensities.

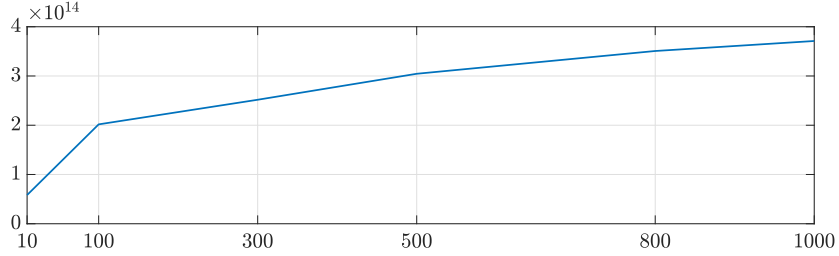


Figure 10: Number of confined particles in the inter-electrode chamber as a function of the Hall parameter  $\|\mathcal{H}_e\|_\infty$ .

- 1 confirms the confinement of the plasma thanks to its magnetization. This confinement
- 2 is also observed on the density and flux profiles along the electrodes
- 3 (Fig. 11). The particles are escaping the inter-electrode chamber along channels
- 4 located in the regions of the magnetic field cusps. The width of these channels is
- 5 narrowed with the increase of the magnetic field intensity. This is qualitatively
- 6 in line with the observations reported in [25].

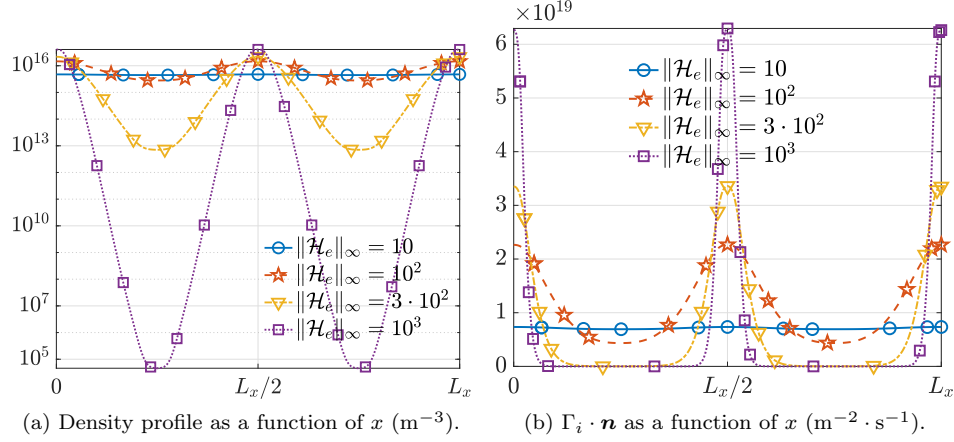


Figure 11: Profile of the plasma density and ionic flux density along the electrodes for different intensities of magnetic field.

#### 1 4.2.2 Inflow versus Augmented Micro-Macro formulations

2 In this section, the loss of symmetry of solutions carried out thanks to the  
3 classical Micro-Macro method is outlined and compared to the outputs of the  
4 augmented version introduced in this work. These two methods differ by the  
5 subset of nodes used to imposing a condition on the auxiliary variable in order to  
6 restore uniqueness of the problem. Classically this condition is set on the subset  
7 of the boundary onto which the magnetic field inflows the domain ( $b \cdot n > 0$ ).  
8 For the magnetic field geometry considered here, this amounts to prescribing  
9 this condition on nodes of the boundary materialized by the red dotted lines on  
10 the plots of Fig. (12a). The discrete problem is therefore non symmetric with  
11 respect to the localization of the nodes where  $q$  is set to 0. This is experienced to  
12 produce numerical approximations inconsistent with the problem symmetries.  
13 The symmetry breakdown accumulates over the iterations, providing the plots  
14 of Fig. 12c representing the profiles of the steady state electric potential on  
15 both electrodes. These curves are non symmetric, similarly to the distribution  
16 on each boundaries of the nodes selected to prescribe the inflow condition  $q = 0$ .

17 The augmented Micro-Macro formulation operates nodes distributed on dif-  
18 ferent locations as plotted on Fig. 12b. The subset  $\partial\Omega_0$  intersects every magnetic  
19 field lines, however with a symmetric distribution in the computational domain.  
20 The augmented formulation offers the possibility to restore the symmetry of  
21 the solution: the curves associated to both electrodes are perfectly matching as  
22 shown on Fig. 12d, the difference of the two profiles being comparable to the  
23 computer arithmetic precision.

24 All the plots presented in Sec. 4.2.1 are related to computations carried out  
25 thanks to the augmented Micro-Macro method.



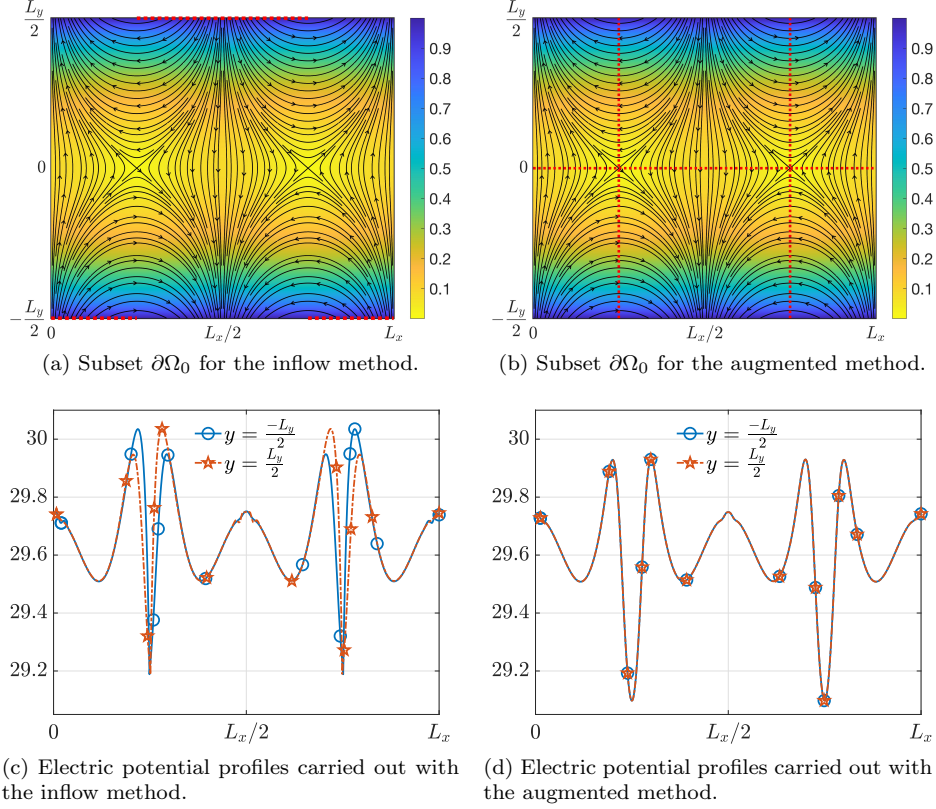


Figure 12: Definition of the subset  $\partial\Omega_0$  (red dotted lines) used to restore the well-posedness of the problem for the inflow (a) and the augmented (b) Micro-Macro (MM) methods; Profiles of the steady state electric potential along the electrodes: blue plain line with circles for  $\phi(x, -L_y/2)$  and red dashed dotted line with pentagrams for  $\phi(x, L_y/2)$ ,  $\|\mathcal{H}_e\|_\infty = 3 \cdot 10^2$ .

#### 1 4.2.3 On the robustness of the numerical model

2 The large depletion of the density inside the quasi-vacuum basins calls into question  
3 the relevance of the quasi-neutrality assumption embedded in the model.  
4 This question is investigated thanks to two diagnostics. The first one is the  
5 scaled Debye length obtained for  $\mathcal{H}_e = 10^3$  as displayed on Fig. 13a. The level-  
6 sets  $\lambda = 1$  plotted on this figure dissociate the validity domain of the quasi-  
7 neutral assumption ( $\lambda \lesssim 1$ ) from regions where the typical scale (the mesh size)  
8 is comparable or smaller to the local (physical) Debye length.

9 The second diagnostic is the ratio of the magnitude of the two contributions  
10 carrying the electric field in the non quasi-neutral model presented in Sec. 2.3.2.  
11 Two distinct inputs are indeed involved in the equation satisfied by the electric

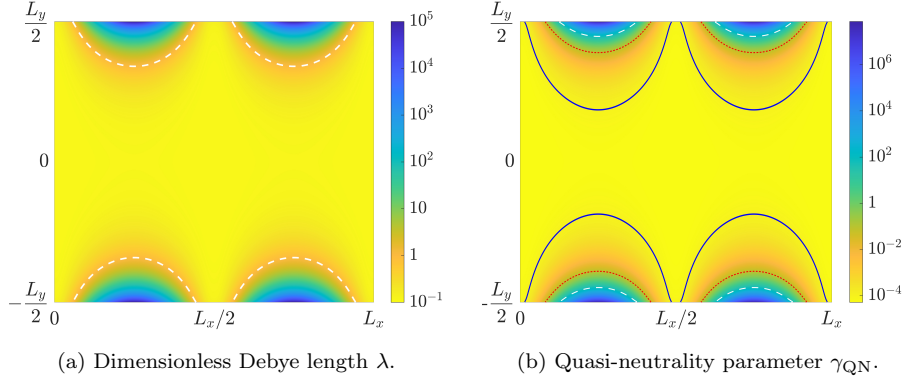


Figure 13: Breakdown of the quasi-neutrality assumption: (a) Dimensionless Debye length in a logarithmic color scale, the level-set  $\bar{\lambda} = 1$  is plotted in a dashed white line; (b) Squared dimensionless Debye length related to the product of the squared electronic Mach number and the number of collisions per typical time  $\gamma_{\text{QN}} = \lambda^2 M_e^2 \kappa_e$  in a color logarithmic scale. The level-sets  $\gamma_{\text{QN}} = 1, 10^3$  and  $10^6$  are plotted in a dashed white, dashed-dotted red and plain blue lines.

1 potential as defined by Eqs. (19). The first one originates from the classical  
 2 isotropic Poisson operator. It is carried by the scaled Debye length in the di-  
 3 mensionless framework introduced herein. The anisotropy is introduced into this  
 4 equation by means of the electronic mobility tensor issued from the divergence  
 5 of the electronic current. This second contribution is proportional to  $1/(M_e^2 \kappa_e)$ .  
 6 The balance between these two contributions is evaluated by  $\gamma_{\text{QN}} = \lambda^2 M_e^2 \kappa_e$ .  
 7 The value of this parameter is plotted on Fig. 13b. It is evaluated thanks to  
 8 the local density, the time step and mesh size being used as typical values for  
 9 the time and length scales. The regions delimited by the electrodes and the  
 10 level-sets  $\gamma_{\text{QN}} = 1$  materialize locations where the non quasi-neutral contribu-  
 11 tion is dominant in Eq. (19a). In between this level-set and the one associated  
 12 to  $\gamma_{\text{QN}} = \varepsilon^{-1} = 10^6$ , the non quasi-neutral (isotropic) contributions exceed  
 13 the magnitude of the diagonal coefficient of the anisotropic tensor in Eq. (19a).  
 14 In other words, non quasi-neutral corrections should significantly decrease the  
 15 anisotropy of this equation in regions delimited by the electrodes and level-set  
 16  $\gamma_{\text{QN}} = \varepsilon^{-1} = 10^6$ , entailing possible changes of the electric field inside the quasi-  
 17 vacuum basins. Contrariwise, in the channels where the particles are flowing  
 18 outside the domain, the quasi-neutral assumption is valid, a feature that should  
 19 be further consolidated for simulations carried out with larger plasma densities.

20 These observations outline that the computations performed herein are quite  
 21 demanding with respect to the anisotropy embedded into the system matrix  
 22 providing the electric potential. Furthermore, this matrix exhibits a condition  
 23 number deteriorating with the vanishing of the density. This is related to the

1 fact that the continuity equation used to carry out the electric potential is close  
2 to singularity because of the small plasma density values. The robustness of the  
3 model shall be pointed out and these difficulties are related to the (quasi-neutral)  
4 model supporting these investigations. These difficulties shall be overcome by  
5 supplementing the model with non quasi-neutral corrections which amounts  
6 to make a step backward in the model hierarchy represented on Fig 1 and  
7 implement the transition from the quasi-neutral drift diffusion model (as defined  
8 in Sec. 2.3.3) to the Drift-Diffusion-Poisson system (Sec. 2.3.2) in which the  
9 quasi-neutral assumption is revoked.

## 10 5 Conclusions

11 In this paper a hierarchy of fluid models is proposed for the simulation of low  
12 temperature plasmas confined by intense magnetic fields. The derivation of these  
13 models unravels the different assumptions embedded in the equations widely im-  
14 plemented for the simulation in the framework of electric propulsion. The issue  
15 related to the approximation of anisotropic problems present in quasi-neutral  
16 modelling of magnetically confined plasmas is addressed by means of asymptotic  
17 preserving methods. These methods provide numerical approximation with an  
18 accuracy unrelated to the anisotropy strength using coordinates and meshes  
19 misaligned with the magnetic direction. A new formulation of the so-called  
20 Micro-Macro method is proposed in order to restore the symmetry of the prob-  
21 lem that is lost in the existing (inflow Micro-Macro) method. The validation  
22 of the augmented method is conducted thanks to an analytic framework. The  
23 method is proved to be accurate regardless of the anisotropy strength. This  
24 method is implemented for the quasi-neutral simulation of a plasma confined  
25 by a cusp-shaped magnetic field, with parameters representative of the electric  
26 propulsion. Though the model remains quite coarse, the confinement of the  
27 plasma is accounted for by the numerical method proposed within this docu-  
28 ment. Nonetheless, a refined description of the ionization process is mandatory.  
29 It is indeed determinant for the plasma dynamics, and strongly related to the  
30 electronic temperature. The model shall therefore be upgraded with an elec-  
31 tronic energy equation, which remains a real challenge for numerical methods.  
32 The electronic dynamics is indeed stiff and strongly anisotropic. This perspec-  
33 tive outlines the tremendous importance of developing numerical methods pre-  
34 cise regardless of the anisotropy strength.

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## 8 References

- 9 [1] A. Alvarez-Laguna. Plasma-sheath transition in multi-fluid models with  
10 inertial terms under low pressure conditions: comparison with the classical  
11 and kinetic theory. *Plasma Sources Sci. Technol.*, page 16, 2020.
- 12 [2] A. Alvarez Laguna, T. Pichard, T. Magin, P. Chabert, A. Bourdon, and  
13 M. Massot. An asymptotic preserving well-balanced scheme for the isother-  
14 mal fluid equations in low-temperature plasmas at low-pressure. *Journal*  
15 *of Computational Physics*, 419:109634, Oct. 2020.
- 16 [3] J. Bareilles, G. J. M. Hagelaar, L. Garrigues, C. Boniface, J. P. Boeuf, and  
17 N. Gascon. Critical assessment of a two-dimensional hybrid Hall thruster  
18 model: Comparisons with experiments. *Physics of Plasmas*, 11(6):3035–  
19 3046, June 2004.
- 20 [4] C. Besse, P. Degond, F. Deluzet, J. Claudel, G. Gallice, and C. Tessieras.  
21 A model hierarchy for ionospheric plasma modeling. *Mathematical Models*  
22 *and Methods in Applied Sciences*, 14(03):393–415, Mar. 2004.
- 23 [5] S. Boccelli, T. Charoy, A. Alvarez Laguna, P. Chabert, A. Bourdon, and  
24 T. E. Magin. Collisionless ion modeling in Hall thrusters: Analytical axial  
25 velocity distribution function and heat flux closures. *Physics of Plasmas*,  
26 27(7):073506, July 2020.
- 27 [6] J.-P. Boeuf. Tutorial: Physics and modeling of Hall thrusters. *Journal of*  
28 *Applied Physics*, 121(1):011101, Jan. 2017.
- 29 [7] J. P. Boeuf and L. Garrigues.  $E \times B$  electron drift instability in Hall  
30 thrusters: Particle-in-cell simulations vs. theory. *Physics of Plasmas*,  
31 25(6):061204, June 2018.
- 32 [8] A. S. Chamarithi, K. Komurasaki, and R. Kawashima. High-order upwind  
33 and non-oscillatory approach for steady state diffusion, advection–diffusion  
34 and application to magnetized electrons. *Journal of Computational Physics*,  
35 374:1120–1151, Dec. 2018.
- 36 [9] T. Charoy, T. Lafleur, A. Tavant, P. Chabert, and A. Bourdon. A com-  
37 parison between kinetic theory and particle-in-cell simulations of anoma-  
38 lous electron transport in  $E \times B$  plasma discharges. *Physics of Plasmas*,  
39 27(6):063510, June 2020.

- 1 [10] R. Chodura. Plasma Flow in the Sheath and the Presheath of a Scrape-Off  
2 Layer. In D. E. Post and R. Behrisch, editors, *Physics of Plasma-Wall*  
3 *Interactions in Controlled Fusion*, pages 99–134. Springer US, Jan. 1986.
- 4 [11] A. Crestetto, F. Deluzet, and D. Doyen. Bridging kinetic plasma descrip-  
5 tions and single-fluid models. *Journal of Plasma Physics*, 86(5), Oct. 2020.
- 6 [12] P. Crispel, P. Degond, and M.-H. Vignal. Quasi-neutral fluid models for  
7 current-carrying plasmas. *Journal of Computational Physics*, 205(2):408–  
8 438, May 2005.
- 9 [13] P. Crispel, P. Degond, and M.-H. Vignal. An asymptotic preserving scheme  
10 for the two-fluid Euler–Poisson model in the quasineutral limit. *Journal of*  
11 *Computational Physics*, 223(1):208–234, Apr. 2007.
- 12 [14] V. Croes. 2D particle-in-cell simulations of the electron drift instability and  
13 associated anomalous electron transport in Hall-effect thrusters. *Plasma*  
14 *Sources Sci. Technol.*, page 15, 2017.
- 15 [15] P. Degond and F. Deluzet. Asymptotic-Preserving methods and multiscale  
16 models for plasma physics. *Journal of Computational Physics*, 336:429–457,  
17 May 2017.
- 18 [16] P. Degond, F. Deluzet, A. Lozinski, J. Narski, and C. Negulescu. Duality-  
19 based Asymptotic-Preserving method for highly anisotropic diffusion equa-  
20 tions. *Commun. Math. Sci.*, 10(1):1–31, 2012.
- 21 [17] P. Degond, F. Deluzet, and C. Negulescu. An asymptotic preserving scheme  
22 for strongly anisotropic elliptic problems. *Multiscale Modeling & Simula-*  
23 *tion. A SIAM Interdisciplinary Journal*, 8(2):645–666, Oct. 2009.
- 24 [18] P. Degond, F. Deluzet, and D. Savelief. Numerical approximation of the  
25 Euler–Maxwell model in the quasineutral limit. *Journal of Computational*  
26 *Physics*, 231(4):1917–1946, Feb. 2012.
- 27 [19] P. Degond, A. Lozinski, J. Narski, and C. Negulescu. An asymptotic-  
28 preserving method for highly anisotropic elliptic equations based on  
29 a Micro-Macro decomposition. *Journal of Computational Physics*,  
30 231(7):2724–2740, 2012.
- 31 [20] F. Deluzet and J. Narski. A Two Field Iterated Asymptotic-Preserving  
32 Method for Highly Anisotropic Elliptic Equations. *Multiscale Modeling &*  
33 *Simulation*, pages 434–459, Jan. 2019.
- 34 [21] S. Günter, Q. Yu, J. Krüger, and K. Lackner. Modelling of heat transport  
35 in magnetised plasmas using non-aligned coordinates. *J. Comput. Phys.*,  
36 209(1):354–370, Oct. 2005.
- 37 [22] G. J. M. Hagelaar. Modelling electron transport in magnetized low-  
38 temperature discharge plasmas. *Plasma Sources Science and Technology*,  
39 16(1):S57, 2007.

- 1 [23] G. J. M. Hagelaar, J. Bareilles, and L. Garrigues. Two-dimensional model  
2 of a stationary plasma thruster. *J. Appl. Phys.*, 91(9):8, 2002.
- 3 [24] J. D. Huba. NRL PLASMA FORMULARY. Technical report, Naval Re-  
4 search Lab., Washington, DC 20375, 2011.
- 5 [25] Y. Jiang, G. Fubiani, L. Garrigues, and J. P. Boeuf. Magnetic cusp con-  
6 finement in low- $\beta$  plasmas revisited. *Physics of Plasmas*, page 14, 2020.
- 7 [26] I. D. Kaganovich, A. Smolyakov, Y. Raiteses, E. Ahedo, I. G. Mikellides,  
8 B. Jorns, F. Taccogna, R. Gueroult, S. Tsikata, A. Bourdon, M. Keidar,  
9 A. T. Powis, M. Merino, M. Cappelli, K. Hara, N. J. Fisch, P. Chabert,  
10 I. Schweigert, T. Lafleur, K. Matyash, A. V. Khrabrov, R. W. Boswell, and  
11 A. Fruchtman. Physics of  $E \times B$  discharges relevant to plasma propulsion  
12 and similar technologies. *Physics of Plasmas*, page 46, 2020.
- 13 [27] R. Kawashima, K. Komurasaki, and T. Schönherr. A hyperbolic-equation  
14 system approach for magnetized electron fluids in quasi-neutral plasmas.  
15 *Journal of Computational Physics*, 284:59–69, Mar. 2015.
- 16 [28] R. Kawashima, K. Komurasaki, and T. Schönherr. A flux-splitting method  
17 for hyperbolic-equation system of magnetized electron fluids in quasi-  
18 neutral plasmas. *Journal of Computational Physics*, 310:202–212, Apr.  
19 2016.
- 20 [29] T. Lafleur, R. Martorelli, P. Chabert, and A. Bourdon. Anomalous electron  
21 transport in Hall-effect thrusters: Comparison between quasi-linear kinetic  
22 theory and particle-in-cell simulations. *Phys. Plasmas*, page 13, 2018.
- 23 [30] I. Levchenko, S. Xu, S. Mazouffre, D. Lev, D. Pedrini, D. Goebel, L. Gar-  
24 rrigues, F. Taccogna, and K. Bazaka. Perspectives, frontiers, and new  
25 horizons for plasma-based space electric propulsion. *Physics of Plasmas*,  
26 27(2):020601, Feb. 2020.
- 27 [31] M. A. Lieberman and A. J. Lichtenberg. *Principles of Plasma Discharges*  
28 *and Materials Processing*. Wiley-Blackwell, Hoboken, N.J, 2nd edition edi-  
29 tion, May 2005.
- 30 [32] A. Lopez Ortega, I. G. Mikellides, M. J. Sekerak, and B. A. Jorns.  
31 Plasma simulations in 2-D (r-z) geometry for the assessment of pole ero-  
32 sion in a magnetically shielded Hall thruster. *Journal of Applied Physics*,  
33 125(3):033302, Jan. 2019.
- 34 [33] I. G. Mikellides and I. Katz. Numerical simulations of Hall-effect  
35 plasma accelerators on a magnetic-field-aligned mesh. *Physical Review E*,  
36 86(4):046703, Oct. 2012.
- 37 [34] A. I. Morozov and V. V. Savelyev. Fundamentals of Stationary Plasma  
38 Thruster Theory. In *Reviews of Plasma Physics*, pages 203–391. Springer  
39 US, Boston, MA, 2000.

- 1 [35] S. Sadouni. *Fluid modeling of transport and instabilities in magnetized low-*  
2 *temperature plasma sources*. Theses, Université Paul Sabatier - Toulouse  
3 III, Feb. 2020.
- 4 [36] R. Sahu, A. R. Mansour, and K. Hara. Full fluid moment model for low  
5 temperature magnetized plasmas. *Physics of Plasmas*, 27(11):113505, Nov.  
6 2020.
- 7 [37] A. Sengupta. Magnetic confinement in a ring-cusp ion thruster discharge  
8 plasma. *J. Appl. Phys.*, 105(9):11, Feb. 2009.
- 9 [38] F. Taccogna and L. Garrigues. Latest progress in Hall thrusters plasma  
10 modelling. *Reviews of Modern Plasma Physics*, 3(1):12, Dec. 2019.
- 11 [39] C. Yang, J. Claustre, and F. Deluzet. Iterative Solvers for Elliptic Problems  
12 with Arbitrary Anisotropy Strengths. *Multiscale Modeling & Simulation*,  
13 16(4):1795–1823, Jan. 2018.
- 14 [40] C. Yang, F. Deluzet, and J. Narski. On the numerical resolution of  
15 anisotropic equations with high order differential operators arising in  
16 plasma physics. *Journal of Computational Physics*, 386:502–523, June 2019.
- 17 [41] C. Yang, F. Deluzet, and J. Narski. Preserving the accuracy of numerical  
18 methods discretizing anisotropic elliptic problems. *arXiv:1911.11482 [cs,*  
19 *math]*, Nov. 2019. arXiv: 1911.11482.

## 20 A Time and space discretizations

We introduce the Cartesian, homogeneous grid of the time-space  $(0, \infty) \times \Omega$

$$((k-1)\Delta t, (i-1)\Delta x, (j-1)\Delta y)_{k \in \mathbb{N}^*, i \in \llbracket 1, N_x \rrbracket, j \in \llbracket 1, N_y \rrbracket}$$

where  $\Delta t$  is the time step,  $\Delta x$  and  $\Delta y$  are the space steps,  $N_x$  and  $N_y$  are positive integers. We set

$$\begin{aligned} \psi_{i,j}^k &= \psi(k\Delta t, i\Delta x, j\Delta y), q_{i,j}^k = q(k\Delta t, i\Delta x, j\Delta y), \quad n_{i,j}^k = n(k\Delta t, i\Delta x, j\Delta y), \\ v_{x,i,j}^k &= v_x(k\Delta t, i\Delta x, j\Delta y), \quad v_{y,i,j}^k = v_y(k\Delta t, i\Delta x, j\Delta y). \end{aligned}$$

The spatial discretization of the electronic system (41) is carried out with the "asymmetric" finite difference scheme proposed in [21, 41]. For a given flux

$$F = \begin{bmatrix} a_{xx} & a_{xy} \\ a_{xy} & a_{yy} \end{bmatrix} \nabla \psi,$$

the finite approximation of  $\nabla \cdot F$  is

$$-\frac{1}{\Delta x} \left( F_{x,i+\frac{1}{2},j} - F_{x,i-\frac{1}{2},j} \right) - \frac{1}{\Delta y} \left( F_{y,i,j+\frac{1}{2}} - F_{y,i,j-\frac{1}{2}} \right),$$

1 where the discrete flux  $[F_{x,i+\frac{1}{2},j} \quad F_{y,i,j+\frac{1}{2}}]^T$  associated to  $F$  are defined at the  
 2 cell interfaces thanks to

$$\left\{ \begin{array}{l} F_{x,i+\frac{1}{2},j} = \frac{a_{xx,i+\frac{1}{2},j}}{\Delta x} (\psi_{i+1,j}^k - \psi_{i,j}^k) \\ \quad + \frac{a_{xy,i+\frac{1}{2},j}}{4\Delta y} ((\psi_{i+1,j+1}^k + \psi_{i,j+1}^k) - (\psi_{i+1,j-1}^k + \psi_{i,j-1}^k)), \\ F_{y,i,j+\frac{1}{2}} = \frac{a_{xy,i,j+\frac{1}{2}}}{4\Delta x} ((\psi_{i+1,j+1}^k + \psi_{i+1,j}^k) - (\psi_{i-1,j}^k + \psi_{i-1,j+1}^k)) \\ \quad + \frac{a_{yy,i,j+\frac{1}{2}}}{\Delta y} (\psi_{i,j+1}^k - \psi_{i,j}^k). \end{array} \right. \quad (44)$$

3 Thanks to that scheme, the approximation of system (41) writes

$$\left\{ \begin{array}{l} -\frac{1}{\Delta x} (F_{x,i+\frac{1}{2},j}^k - F_{x,i-\frac{1}{2},j}^k) \\ \quad - \frac{1}{\Delta y} (F_{y,i,j+\frac{1}{2}}^k - F_{y,i,j-\frac{1}{2}}^k) + \mathcal{L}_{i_0,j_0}^k = S_{i,j}^k, \\ -\frac{1}{\Delta x} (G_{x,i+\frac{1}{2},j}^k - G_{x,i-\frac{1}{2},j}^k) - \frac{1}{\Delta y} (G_{y,i,j+\frac{1}{2}}^k - G_{y,i,j-\frac{1}{2}}^k) = 0, \\ q_{i_0,j_0} = 0, \\ F_{x,\frac{1}{2},j}^k = 0, \quad F_{x,N_x-\frac{1}{2},j}^k = 0, \quad q_{1,j} = 0, \quad q_{N_x,j} = 0, \\ F_{y,i,\frac{1}{2}}^k = - \left[ \Gamma_\beta \left( -\psi + k_B T_e \ln \left( \frac{n}{n_0} \right) \right) \right]_{i,\frac{1}{2}}^k, \quad G_{y,i,\frac{1}{2}}^k = 0, \\ F_{y,i,N_y-\frac{1}{2}}^k = \left[ \Gamma_\beta \left( -\psi + k_B T_e \ln \left( \frac{n}{n_0} \right) \right) \right]_{i,N_y-\frac{1}{2}}^k, \quad G_{y,i,N_y-\frac{1}{2}}^k = 0, \end{array} \right. \quad (45)$$

where  $(i_0, j_0) \in \mathcal{I}_0$ ,  $\mathcal{I}_0$  being a subset of  $\llbracket 1, N_x \rrbracket \times \llbracket 1, N_y \rrbracket$  discretizing  $\partial\Omega_0$  and  
 $[F_{x,i+\frac{1}{2},j}^k \quad F_{y,i,j+\frac{1}{2}}^k]^T$  and  $[G_{x,i+\frac{1}{2},j}^k \quad G_{y,i,j+\frac{1}{2}}^k]^T$  are discrete fluxes associated  
 to

$$F^k = \mu n^k \varepsilon \nabla_{\parallel} q + \mu n^k \varepsilon \nabla_{\perp} \psi \quad \text{and} \quad G^k = \mu n^k \varepsilon \nabla_{\parallel} q - \mu n^k \nabla_{\parallel} \psi,$$

4 defined accordingly to Eqs. (44).

5 System (1) describing the evolution of the ions is discretized by means of a  
 6 Rusanov scheme

$$\left\{ \begin{array}{l} n_{i,j}^{k+1} = n_{i,j}^k - \frac{\Delta t}{\Delta x} (H_{x,i+\frac{1}{2},j}^k - H_{x,i-\frac{1}{2},j}^k) - \\ \quad \frac{1}{\Delta y} (H_{y,i,j+\frac{1}{2}}^k - H_{y,i,j-\frac{1}{2}}^k) + \Delta t S_{i,j}^k, \\ n_{1,j}^{k+1} = n_{2,j}^{k+1}, \quad n_{N_x,j}^{k+1} = n_{N_x-1,j}^{k+1}, \\ n_{i,1}^{k+1} = \frac{n_{i,2}^k v_{y,i,2}^k}{v_B}, \quad n_{i,N_y}^{k+1} = \frac{n_{i,N_y-1}^k v_{y,i,N_y-1}^k}{v_B}, \end{array} \right. \quad (46)$$



$$\left\{ \begin{array}{l} n_{i,j}^{k+1} v_{x,i,j}^{k+1} = n_{i,j}^k v_{x,i,j}^k \frac{\Delta t}{\Delta x} \left( M_{x,i+\frac{1}{2},j}^k - M_{x,i-\frac{1}{2},j}^k \right) - \\ \quad - \frac{\Delta t}{\Delta y} \left( M_{y,i,j+\frac{1}{2}}^k - M_{y,i,j-\frac{1}{2}}^k \right) + \frac{e\Delta t}{m_i} n_{i,j}^k E_{x,i,j}^k, \\ n_{i,j}^{k+1} v_{y,i,j}^{k+1} = n_{i,j}^k v_{y,i,j}^k - \frac{\Delta t}{\Delta x} \left( L_{x,i+\frac{1}{2},j}^k - L_{x,i-\frac{1}{2},j}^k \right) \\ \quad - \frac{\Delta t}{\Delta y} \left( L_{y,i,j+\frac{1}{2}}^k - L_{y,i,j-\frac{1}{2}}^k \right) + \frac{e\Delta t}{m_i} n_{i,j}^k E_{y,i,j}^k, \\ v_{x,1,j}^{k+1} = 0, \quad v_{x,N_x,j}^{k+1} = 0, \quad v_{y,i,1}^{k+1} = -1, \quad v_{y,i,N_y}^{k+1} = 1, \end{array} \right. \quad (47)$$

where

$$\begin{aligned} H_{x,i+\frac{1}{2},j}^k &= n_{i+1,j}^k v_{x,i+1,j}^k + n_{i,j}^k v_{x,i,j}^k + \Lambda_{i+\frac{1}{2},j}^k (n_{i+1,j}^k - n_{i,j}^k), \\ H_{y,i,j+\frac{1}{2}}^k &= n_{i,j+1}^k v_{y,i,j+1}^k + n_{i,j}^k v_{y,i,j}^k + \Lambda_{i,j+\frac{1}{2}}^k (n_{i,j+1}^k - n_{i,j}^k), \\ M_{x,i+\frac{1}{2},j}^k &= n_{i+1,j}^k v_{x,i+1,j}^k v_{x,i+1,j}^k + n_{i,j}^k v_{x,i,j}^k v_{x,i,j}^k + \\ &\quad \Lambda_{i+\frac{1}{2},j}^k (n_{i+1,j}^k v_{x,i+1,j}^k - n_{i,j}^k v_{x,i,j}^k), \\ L_{x,i+\frac{1}{2},j}^k &= n_{i+1,j}^k v_{y,i+1,j}^k v_{x,i+1,j}^k + n_{i,j}^k v_{y,i,j}^k v_{x,i,j}^k + \\ &\quad \Lambda_{i+\frac{1}{2},j}^k (n_{i+1,j}^k v_{y,i+1,j}^k - n_{i,j}^k v_{y,i,j}^k), \end{aligned}$$

the fluxes  $M_{y,i,j+\frac{1}{2}}^k$  and  $L_{y,i,j+\frac{1}{2}}^k$  being defined similarly, and

$$\Lambda_{i+\frac{1}{2},j}^k = \frac{\Delta t}{2\Delta x} (2 + |v_{x,i+1,j}^k| + |v_{x,i,j}^k|), \quad \Lambda_{i,j+\frac{1}{2}}^k = \frac{\Delta t}{2\Delta y} (2 + |v_{y,i,j+1}^k| + |v_{y,i,j}^k|).$$

- 2 The numerical viscosity of the scheme is lower bounded by a positive value,  
3 arbitrarily set to 1, to ensure the stability of the scheme in regions where the  
4 plasma may be at rest. The value of this threshold has not been experienced to  
5 be significant in the simulation outputs.

The approximation of the electric field  $E = -\nabla\phi$  is defined as

$$E_{x,i+1/2,j}^k = -\frac{\phi_{i+1,j} - \phi_{i,j}}{\Delta x} \quad \text{and} \quad E_{y,i,j+1/2}^k = -\frac{\phi_{i,j+1} - \phi_{i,j}}{\Delta y}.$$