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► **To cite this version:**

Fabrice Deluzet, Jacek Narski, Moctar Ndiaye, Gerjan Hagelaar, Jean-Pierre Boeuf. Numerical methods and macroscopic models of magnetically confined plasmas for propulsion. *Kinetic and Related Models*, 2023, 16 (5), pp.624-653. 10.3934/krm.2023002 . hal-03622154

HAL Id: hal-03622154

<https://hal.science/hal-03622154v1>

Submitted on 28 Mar 2022

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

3 F. Deluzet^{‡*}, J. Narski[‡], M. Ndiaye[‡], G. Hagelaar[†], J. Boeuf[†]

[‡]Université de Toulouse; UPS, INSA, UT1, UTM,
Institut de Mathématiques de Toulouse,
CNRS, Institut de Mathématiques de Toulouse UMR 5219,
F-31062 Toulouse, France,
forname.name@math.univ-toulouse.fr

[†]LAPLACE, Université de Toulouse, CNRS, INPT, UPS,
118 Route de Narbonne, 31062 Toulouse, France
forname.name@laplace.univ-tlse.fr

* Corresponding author.

4 March 25, 2022

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-

*Corresponding author

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 α , 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_α 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: ν_α is the collision frequency of the
 26 specie α 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 ε_0 being the vacuum permittivity. The electric field is deduced from the elec-
 6 trostatic potential ϕ 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 μ_α , the Hall parameter \mathcal{H}_α for the species α 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 α is
 20 denoted \bar{T}_α 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

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

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 α ;
$\eta = \frac{e \bar{x} \bar{E}}{k_B \bar{T}_e}$	electric energy related to the electronic internal energy.

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

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

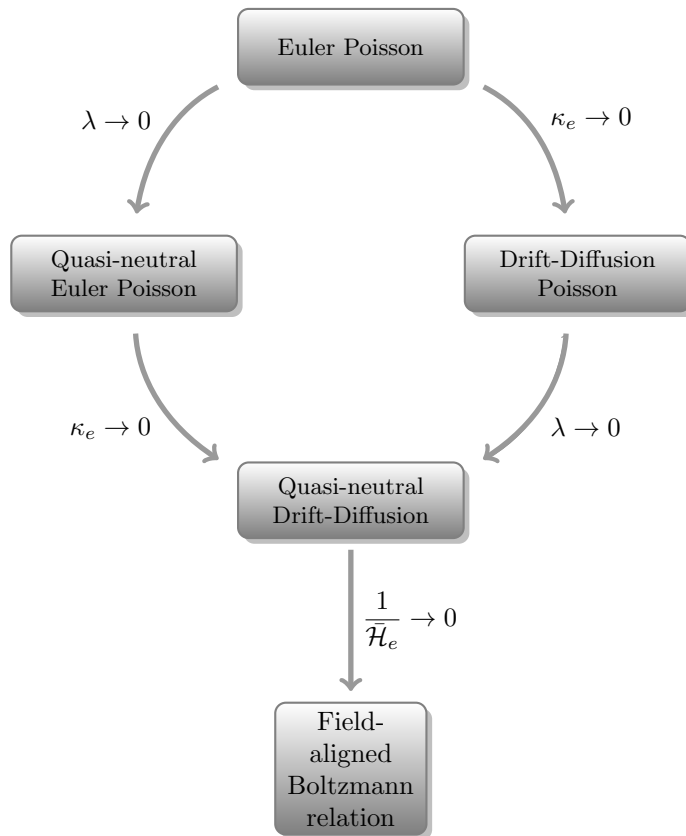


Figure 1: Hierarchy of (isothermal) fluid models.

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 $\mathcal{H}_e = \nu_e \bar{\mathcal{H}}_e$, 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 Ξ , 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 λ^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 ψ 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 , ϕ_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 Γ_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 $\mu_{\parallel} = \mu_e = em_e/\nu_e$, ν_e being the collision frequency against neutral,
 7 and the Perderson mobility $\mu_P = \mu_e\varepsilon$. The anisotropic parameter ε 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 ν 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 ψ 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 β 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 ϕ

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

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

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

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 Γ'_β is the derivative of Γ_β , 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 Δ_\parallel^h and Δ_\perp^h , Ψ^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 ε -values can therefore be anticipated, precisely a linear
 9 growth of the error with ε^{-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 ψ 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 Ω 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 (ψ, 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

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

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

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

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

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

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

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

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

4 Demonstrative calculations

4.1 Validation of the augmented Micro-Macro method

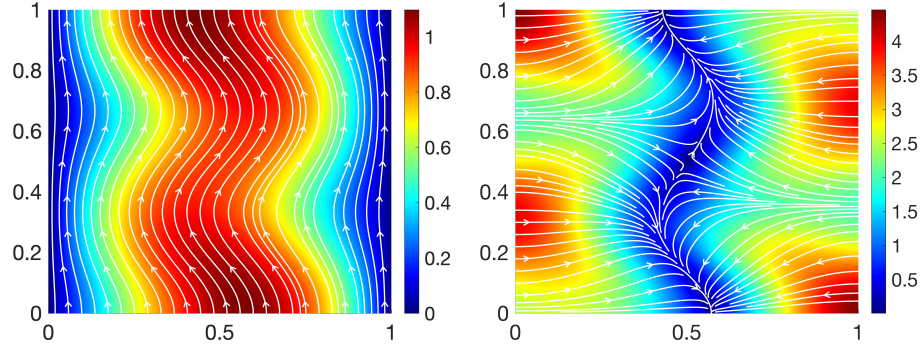
In this section, the capability of the elliptic problem solver to recover a precise approximation of the force field and potential (\mathcal{F} and ψ), irrespective to the anisotropy strength, is examined. In this aim, a manufactured solution of the toy model defined by Eqs. (35) is therefore proposed.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

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

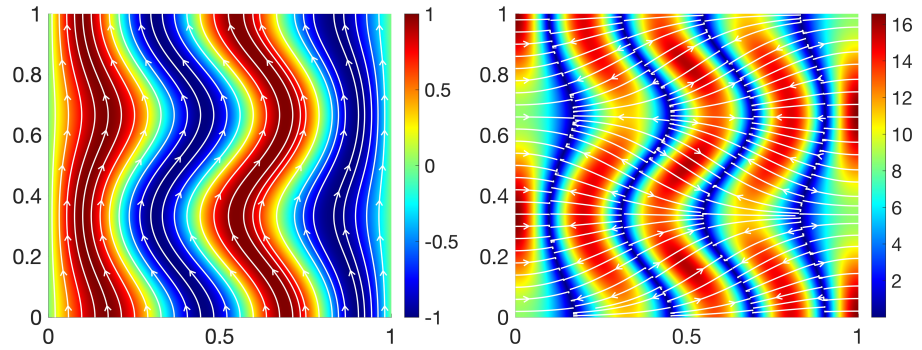
The manufactured solution for the potential, denoted ψ_m , is defined by means of two components ψ_0 and ψ_1 with

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

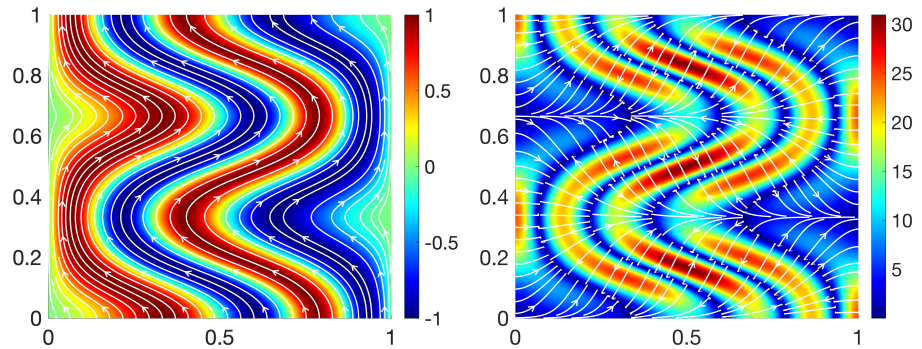
The curvature of the magnetic field is parametrized by $\zeta \in \mathbb{R}$, $\zeta \geq 0$. The second parameter, $k \in \mathbb{N}$, provides a control of the perpendicular gradient of the solution in the limit $\varepsilon \rightarrow 0$, the variations of the solution perpendicular to the magnetic field being reduced to that of ψ_0 for large anisotropy strengths. The set-up associated to the manufactured solution is illustrated on the plots of Fig. 2. The auxiliary variable is set to zero along an horizontal line intersecting any field line, at the bottom ($y = 0$ or the top $y = 1$) of the computational 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 (ψ) 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

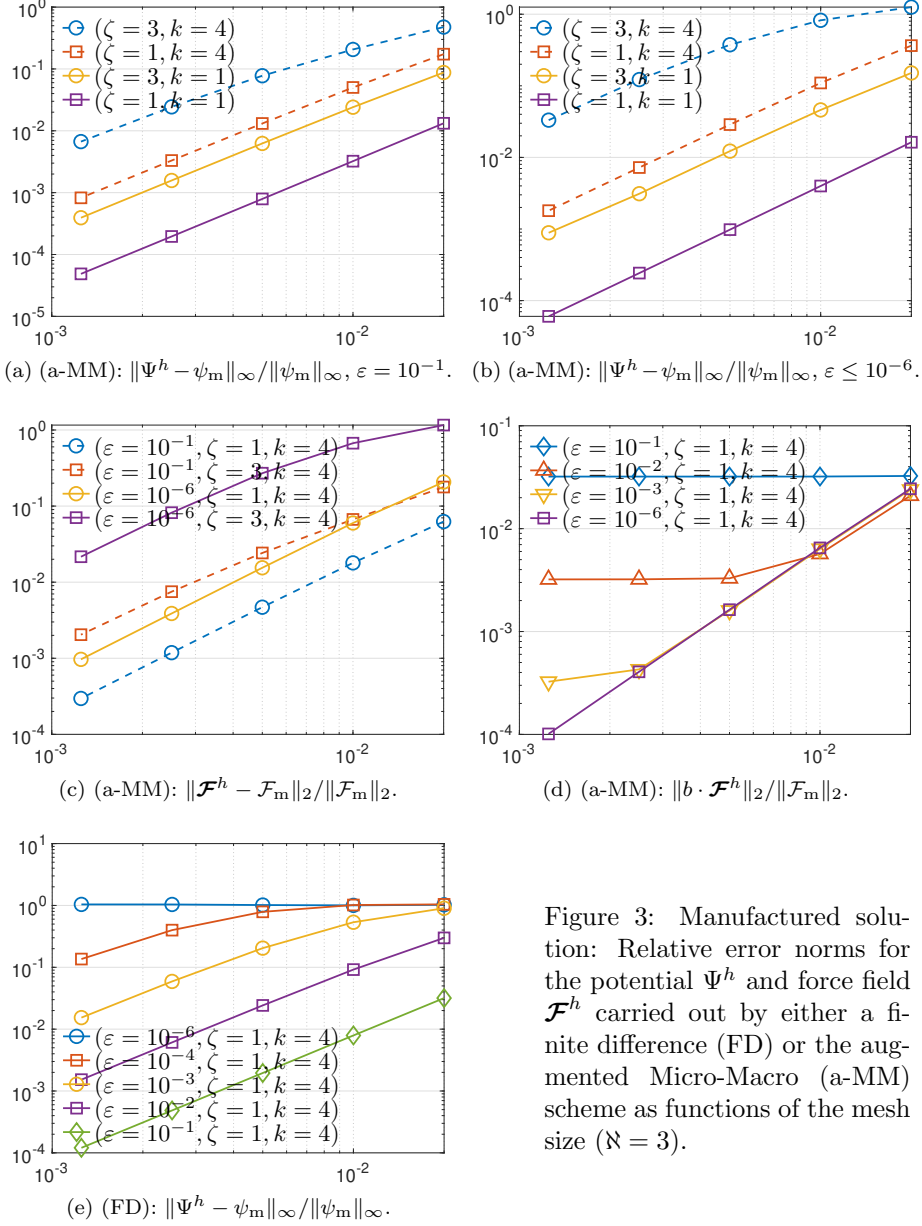


Figure 3: Manufactured solution: Relative error norms for the potential Ψ^h and force field \mathcal{F}^h carried out by either a finite difference (FD) or the augmented Micro-Macro (a-MM) scheme as functions of the mesh size ($\aleph = 3$).

2
3 accuracy of Ψ^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 ε -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 ε (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 ε^{-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 ε 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.

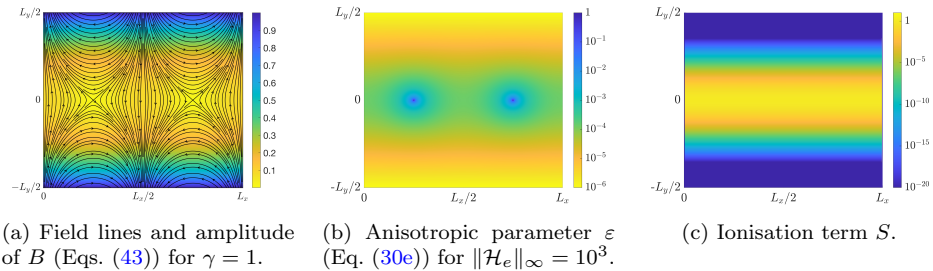


Figure 4: Set-up for plasma confinement by a cusp-shaped magnetic field.

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 399×399 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 ψ the solution of
 the anisotropic problem as displayed on Fig. 5. This variable is almost constant

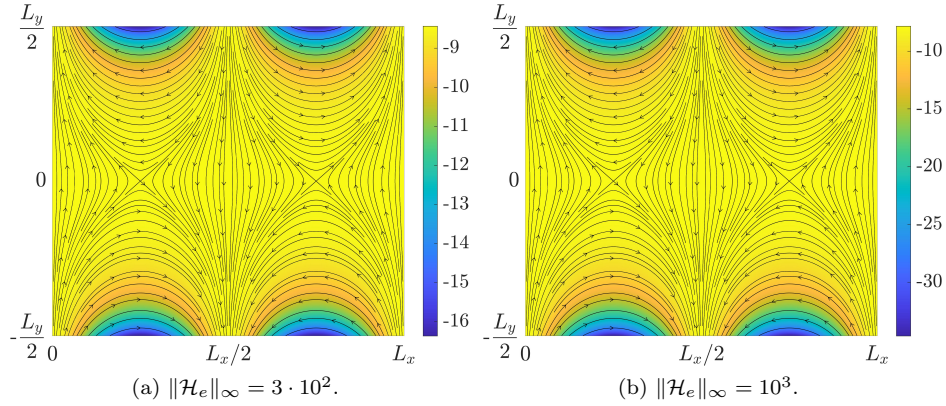


Figure 5: Solution of the anisotropic problem ψ ($\text{V} \cdot \text{m}^{-1}$) in a color scale and magnetic field lines carried out with different intensities of magnetic field.

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

26 The confinement of the plasma may be assessed by the space integral of
 27 the 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

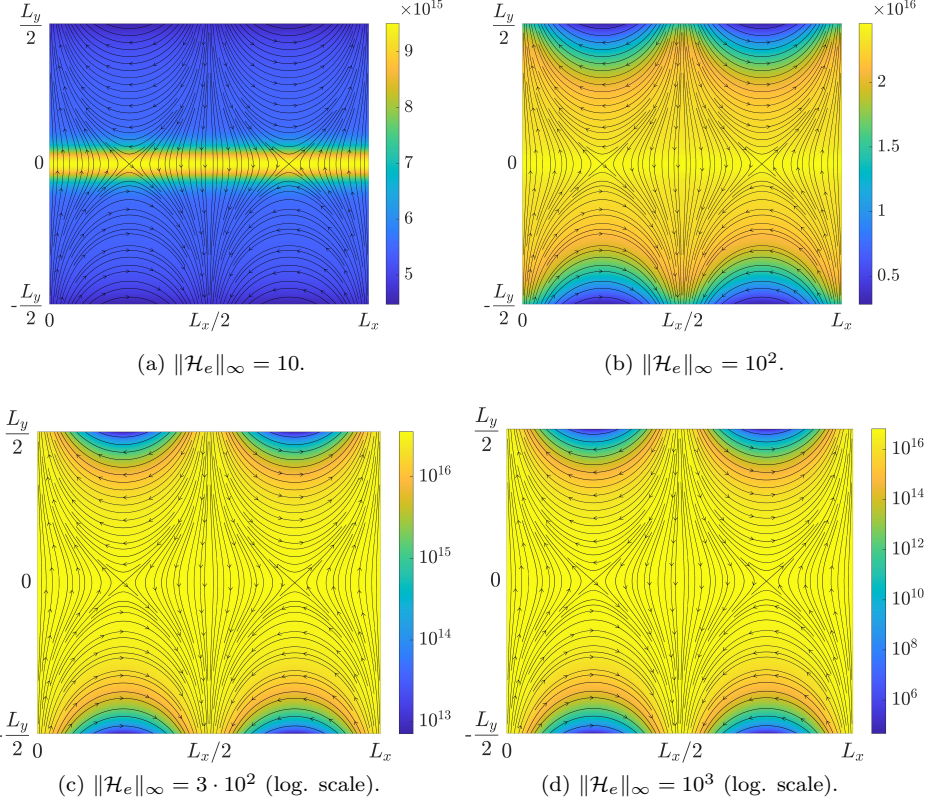


Figure 6: Plasma density (in a logarithmic color scale for subplots (c) and (d)) and magnetic field lines carried out with different intensities of magnetic field.

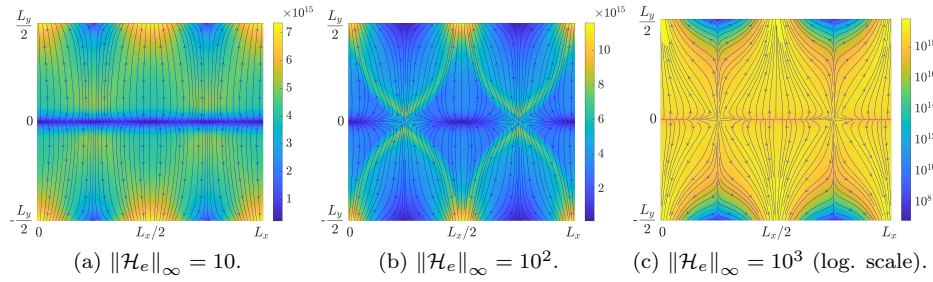


Figure 7: Electronic flux density $\Gamma_e = nu_e$ ($\text{m}^{-2} \cdot \text{s}^{-1}$) for different magnetisation intensities.

- 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

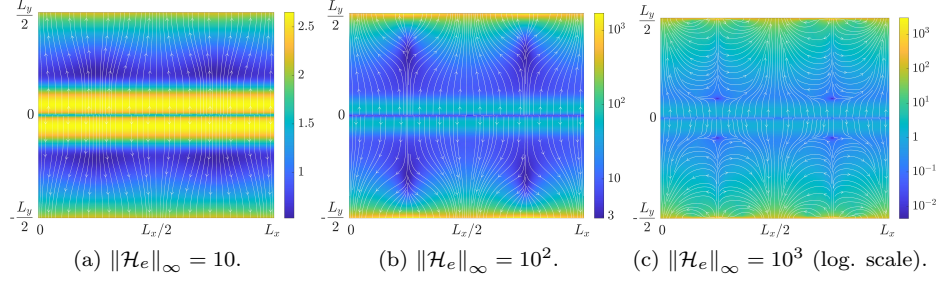


Figure 8: Electric field magnitude ($\text{V} \cdot \text{m}^{-1}$) in a color scale and associated field lines for different magnetisation intensities.

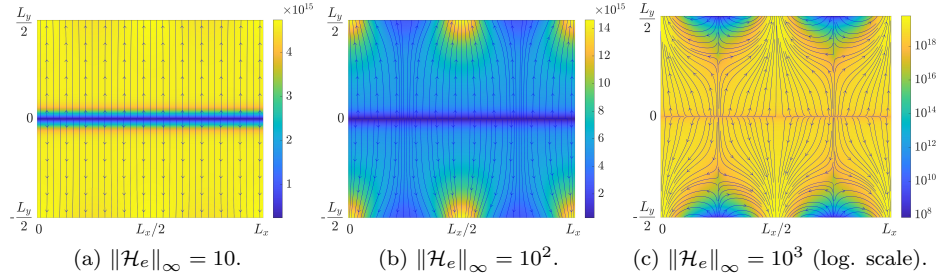


Figure 9: Ionic flux density $\Gamma_i = nu_i$ ($\text{m}^{-2} \cdot \text{s}^{-1}$) for different magnetisation intensities.

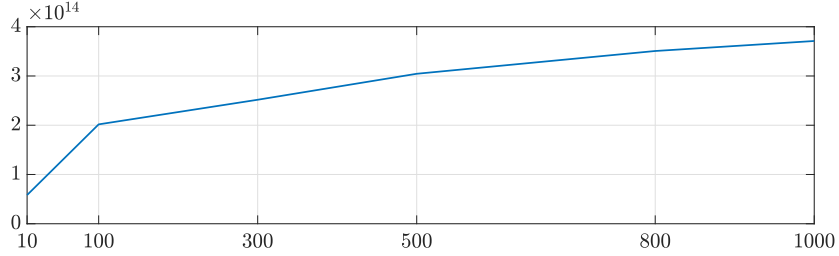


Figure 10: Number of confined particles in the inter-electrode chamber as a function of the Hall parameter $\|\mathcal{H}_e\|_\infty$.

- 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].

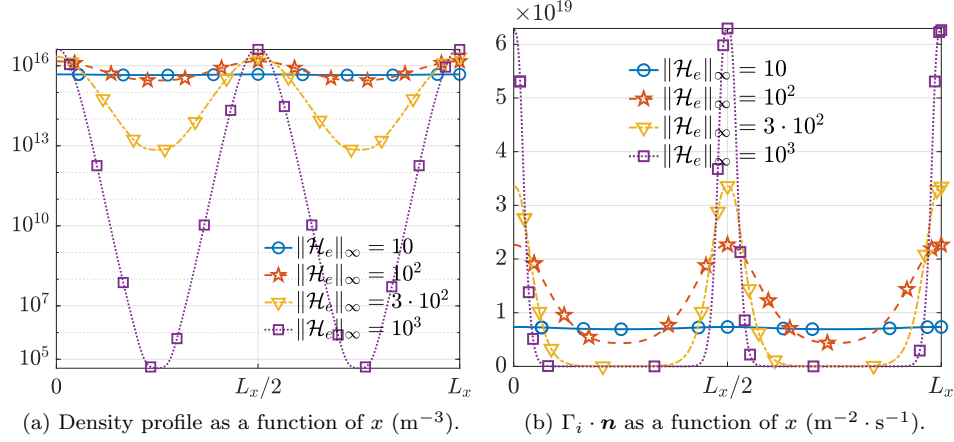


Figure 11: Profile of the plasma density and ionic flux density along the electrodes for different intensities of magnetic field.

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 ($b \cdot \mathbf{n} > 0$).
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 the
21 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.

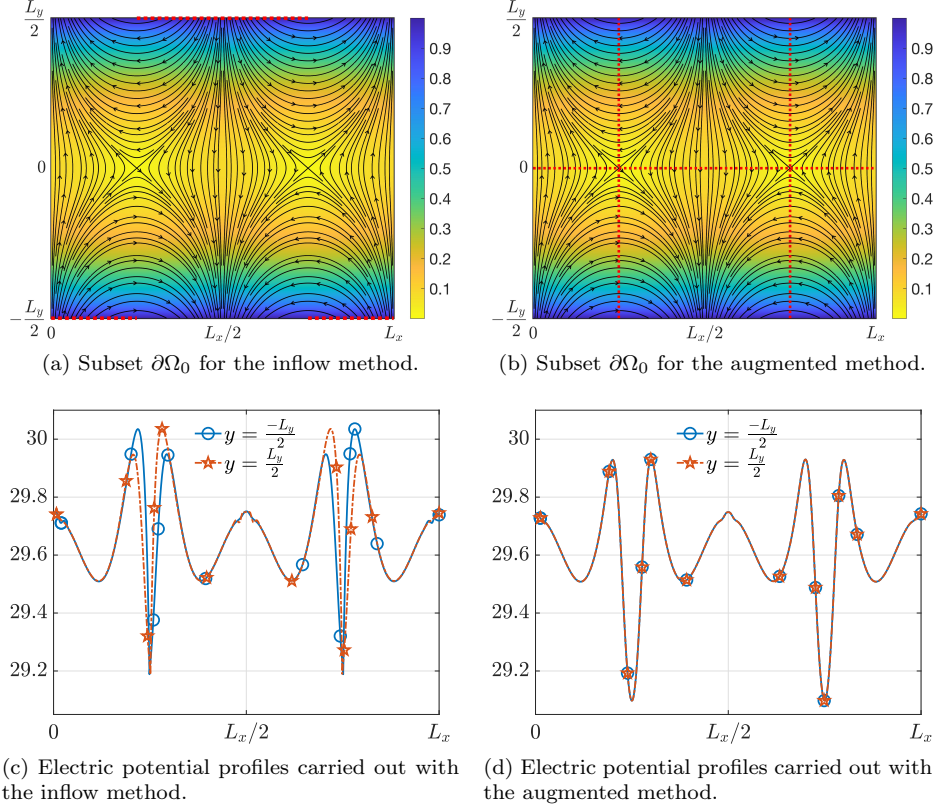


Figure 12: Definition of the subset $\partial\Omega_0$ (red dotted lines) used to restore the well-posedness of the problem for the inflow (a) and the augmented (b) Micro-Macro (MM) methods; Profiles of the steady state electric potential along the electrodes: blue plain line with circles for $\phi(x, -L_y/2)$ 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

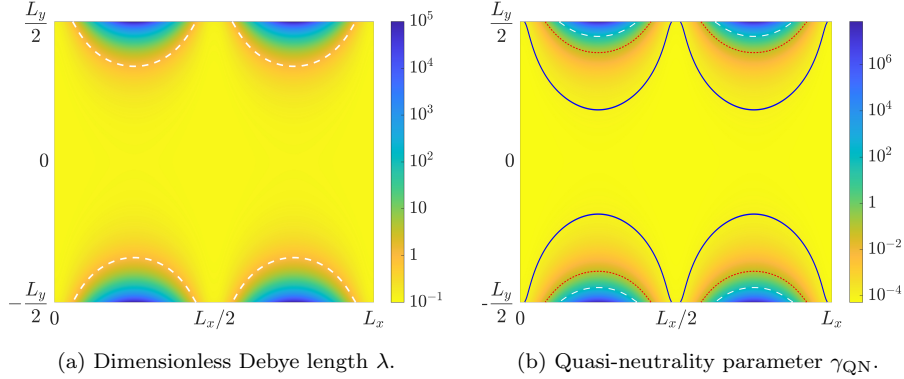


Figure 13: Breakdown of the quasi-neutrality assumption: (a) Dimensionless Debye length in a logarithmic color scale, the level-set $\bar{\lambda} = 1$ is plotted in a dashed white line; (b) Squared dimensionless Debye length related to the product of the squared electronic Mach number and the number 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.

35 Acknowledgements

36 This work has been supported by the RTRA STAE fondation in the frame of
37 the INNPULSE project (InNovative CoNcepts for Plasma PropULsion in Space)
38 and by a public grant from the “Laboratoire d’Excellence Centre International
39 de Mathématiques et d’Informatique” (LabEx CIMI) overseen by the French
40 National Research Agency (ANR) as part of the “Investissements d’Avenir”

1 program (reference ANR-11-LABX-0040) in the frame of the PROMETEUS
2 project (PRospect of nOvel nuMerial modElS for elecTric propulsion and low
3 tEmperatUre plaSmas).
4 F.D. and J.N. acknowledge support from the FrFCM (Fédération de recherche
5 pour la Fusion par Confinement Magnétique) in the frame of the NEMESIA
6 project (Numerical mEthods for Macroscopic models of magnEtized plaSmas
7 and related anIsotropic equAtions).

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- β plasmas revisited. *Physics of Plasmas*, page 14, 2020.
- 7 [26] I. D. Kaganovich, A. Smolyakov, Y. Raitsev, 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 Δt is the time step, Δx and Δy 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

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