LINEARIZED ELECTRODYNAMICS AND STABILIZATION OF A COLD MAGNETIZED PLASMA

SIMON LABRUNIE$^{1}$ and IBTISSEM ZAAFRANI$^{1,2}$

Abstract. We consider a linearized Euler–Maxwell model for the propagation and absorption of electromagnetic waves in a magnetized plasma. We present the derivation of the model, and we show its well-posedness, its strong and polynomial stability under suitable and fairly general assumptions, its exponential stability in the same conditions as the Maxwell system, and finally its convergence to the time-harmonic regime. No homogeneity assumption is made, and the topological and geometrical assumptions on the domain are minimal. These results appear strongly linked to the spectral properties of various matrices describing the anisotropy and other plasma properties.

Résumé. Nous considérons un modèle d’Euler–Maxwell linéarisé pour la propagation et l’absorption des ondes électromagnétiques dans un plasma magnétique. Nous établissons les équations du modèle, puis nous montrons sa bonne position, sa stabilité forte et polynomial sous des hypothèses assez générales, ainsi que la stabilité exponentielle dans les mêmes conditions que le système de Maxwell, ainsi que la convergence vers le régime harmonique en temps. Aucune hypothèse d’homogénéité n’est faite, et les hypothèses topologiques et géométriques sur le domaine sont minimales. Ces résultats semblent fortement liés aux propriétés spectrales de diverses matrices décrivant l’anisotropie et d’autres propriétés du plasma.

1991 Mathematics Subject Classification. 35Q61, 35B40, 37L15, 47D06, 93D20, 93D23.

January 7, 2021.

1. INTRODUCTION

Electromagnetic wave propagation in plasmas, especially magnetized ones, is a vast subject [24]. Even in a linear framework, the equations that describe it are generally highly anisotropic and, in many practical settings, highly inhomogeneous as well. The bewildering array of phenomena and parameters involved in this modelling requires to derive simplified models tailored to the phenomenon under study, and to the theoretical or computational purpose of this study.

Wave-plasma interaction is of paramount importance, for instance, in tokamak technology. According to their frequency, electromagnetic waves can be used in a wide range of processes: to stabilize or heat the
plasma and thus bring it closer to the conditions needed for nuclear fusion, for instance, or to probe various properties such as density and temperature. These interactions involve many phenomena, such as propagation, absorption, refraction, scattering, etc. The basic physics is well understood [24]; nevertheless, efficient and robust mathematical models have to be derived in order to do reliable numerical simulations in realistic settings, or to properly interpret experimental results.

A first, time-harmonic model focused on propagation and absorption has been derived in [4, 13]. This article constitutes the time-dependent counterpart of those works. We consider a general linearized Euler–Maxwell model describing the interaction between a strongly magnetized, pressureless, totally ionized gas and an electromagnetic wave; it can be particularized to various physical settings. The waves accelerate the charged particles that make up the plasma, and transfer some of their energy to them through collisions, which act as friction. We study the well-posedness of the model, investigate various stability properties (strong, polynomial, and exponential), and finally check that no inconsistency stems from the time-harmonic modelling. The latter appears, as expected, as a particular solution and a limit of the general solution (under reasonable physical assumptions) in presence of a time-harmonic forcing. Not only the time-dependent model is more general, but it also appears more robust. The well-posedness of the time-harmonic model rests upon absorption; more exactly, the proof fails in the absence of absorption, and serious qualitative arguments suggest that the limiting model is actually ill-posed [4].

On the other hand, we shall see that the time-dependent model is well-posed even without absorption. Nevertheless, and unsurprisingly, the convergence (exponential or polynomial) of the time-dependent model toward the time-harmonic one does depend on absorption. The mathematical tools used in this analysis are well-known theorems on semigroups and operator spectra [2, 14, 17, 23]. The main difficulties are: first, the resolvent of the evolution operator is not compact; then, absorption only acts on some variables, namely, the hydrodynamic ones; finally, one has to handle with various technicalities linked to inhomogeneity, anisotropy, and topology. More or less similar models have been studied by various authors [18, 19, 25]; but they did not include anisotropy or inhomogeneity, and they generally considered simpler topologies or boundary conditions than we do. On the contrary, we have tried to keep our model as general as possible, by assuming neither any homogeneity in the plasma properties, nor in the external magnetic field, nor any strong topological or geometrical condition on the domain.

Generally speaking, stabilization and controllability of Maxwell’s equations and coupled models involving them may be rooted in two main physical mechanisms: boundary stabilization of the sourceless Maxwell system through an absorbing boundary condition on all or part of the boundary [5, 11, 15, 20, 22, among others]; or internal stabilization by some resistive source term on all or part of the domain, typically that given by Ohm’s law [22, among others]. Boundary absorption is usually sufficient to have energy decay and convergence toward an equilibrium state (strong stability [5]), but the precise decay rate (polynomial or exponential stability) strongly depends on the global shape of the domain (various star-shapedness conditions such as [15,20]) and/or the absorbing part of the boundary (geometric control condition [22]). Internal absorption, when it only holds on part of the domain, also requires a geometric control condition [22]. Mathematically, the issue has been tackled by several approaches: the multiplier method [11,15, etc.], microlocal analysis [22, etc.], or frequency-domain analysis [19]. In this paper we use the later method, and we focus on internal stabilisation; the internal absorption mechanism, however, is different from Ohm’s law. This allows us to consider fairly arbitrary geometries and topologies, provided some physically reasonable (in the framework of tokamak plasmas) assumption holds (Hypothesis 2 below; cf. [4, Remark 4.1]). The complementary approach, where the physical hypotheses are weakened at the price of stricter conditions on the geometry, is reserved for future work.

The outline of the article is as follows. In §2, we present the derivation of the model, and recall some classical results on the functional analysis of Maxwell’s equations in §3. Section 4 is devoted to the proof of the well-posedness of the model, in three variants: with a perfectly conducting condition on the whole boundary, and with a Silver–Müller one (homogeneous or not) on part of it. Section 5 recalls or introduces some more advanced results of functional analysis, which are needed in the sequel. In §6, we study the spectral properties
of various matrices describing the anisotropy and other plasma properties, which will be essential in the stability proofs of §§7 and 8. The former is dedicated to strong stability, the latter to unconditional polynomial and conditional exponential stability. Though it happens that the polynomial stability does not entail stronger hypotheses than strong one, we have chosen to present them sequentially: the results which allow us to prove strong stability are also the starting point for the finer properties needed to prove polynomial and exponential stability. The stability part is also divided into perfectly conducting and Silver–Müller boundary conditions. As an application, we conclude with a result of convergence to the time-harmonic regime when the Silver–Müller boundary data is time-harmonic.

2. The model

The physical system we are interested in is a plasma or totally ionized gas, pervaded by a strong, external, static magnetic field $B_{\text{ext}}(x)$, which makes the medium anisotropic. The sources of this field are assumed to be outside the plasma. Such a medium can be described as a collection of charged particles (electrons and various species of ions) which move in vacuum and create electromagnetic fields which, in turn, affect their motion. Electromagnetic fields are, thus, governed by the usual Maxwell’s equations in vacuum:

$$\begin{align*}
\text{curl} \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}, \\
\varepsilon_0 \text{curl} \mathbf{B} &= \frac{\mathbf{J}}{\varepsilon_0} + \frac{\partial \mathbf{E}}{\partial t}, \\
\text{div} \mathbf{E} &= \frac{\rho}{\varepsilon_0}, \\
\text{div} \mathbf{B} &= 0.
\end{align*}$$

Here $\mathbf{E}$ and $\mathbf{B}$ denote the electric and magnetic fields; $\rho$ and $\mathbf{J}$ the electric charge and current densities; $\varepsilon_0$ is the electric permittivity, and $c$ the speed of light, in vacuum.

The electromagnetic field is the sum of a static part and a small perturbation caused by the penetration of an electromagnetic wave. To simplify the discussion, we assume the plasma to be in mechanical and electrostatic equilibrium in the absence of the wave. Thus, the electric and magnetic fields can be written as:

$$\begin{align*}
\mathbf{E}(t, x) &= \epsilon \mathbf{E}(t, x), & \text{and} & & \mathbf{B}(t, x) &= \mathbf{B}_{\text{ext}}(x) + \epsilon \mathbf{B}(t, x),
\end{align*}$$

where $\epsilon \ll 1$ is the perturbation parameter. The total charge and current densities associated with the fields are those due to the perturbation

$$\begin{align*}
\rho(t, x) &= \epsilon \rho(t, x), & \text{and} & & \mathbf{J}(t, x) &= \epsilon \mathbf{J}(t, x).
\end{align*}$$

The static parts of $\mathbf{E}$, $\rho$ and $\mathbf{J}$ are zero by the equilibrium assumption.

Furthermore, we assume the plasma to be cold, i.e., the thermal agitation of particles, and thus their pressure, is negligible. We shall designate the particles species (electrons and various species of ions) with the index $s$. We denote as $q_s$ the charge of one particle and $m_s$ its mass. The momentum conservation equation of particles of the species $s$ writes:

$$m_s \frac{\partial \mathbf{U}_s}{\partial t} + m_s (\mathbf{U}_s \cdot \nabla) \mathbf{U}_s - q_s (\mathbf{E} + \mathbf{U}_s \times \mathbf{B}) + m_s \nu_s \mathbf{U}_s = 0,$$

where $\mathbf{U}_s$ denotes the fluid velocity and $\nu_s \geq 0$ is the collision frequency which only depends on the variable $x$. The charge and current densities can be expressed as a function of the particle densities $n_s(t, x)$ and the fluid velocities:

$$\rho = \sum_s q_s n_s, \quad \mathbf{J} = \sum_s \mathbf{J}_s = \sum_s q_s n_s \mathbf{U}_s.$$
Now, multiplying Equation (4) by \( \frac{n_s q_s}{m_s} \), we get
\[
\frac{\partial J_s}{\partial t} + \frac{1}{\varrho_s} (J_s \cdot \nabla) J_s - \frac{q_s}{m_s} (\varrho_s E + J_s \times B) + \nu_s J_s = 0.
\] (5)

We now linearize Equation (5). From the above discussion, we can assume, for each species \( s \),
\[
\varrho_s(t, x) = q_s n_0^0(x) + \epsilon \rho_s(t, x), \quad \text{and} \quad J_s(t, x) = \epsilon J_s(t, x),
\]
where \( n_0^0 \) is the equilibrium particle density, assumed to depend on \( x \) only. On the left-hand side of (5), the terms of order 0 in \( \epsilon \) vanish. To express the terms of order 1, we introduce the plasma and cyclotron frequencies for the species \( s \), respectively:
\[
\omega_{ps} := \sqrt{\frac{n_0^0 q_s^2}{\varepsilon_0 m_s}}, \quad \Omega_{cs} := \frac{q_s |B_{ext}|}{m_s};
\] (6)
they only depend on the space variable \( x \). Observe that the cyclotron frequency is signed: it has the same sign as the charge \( q_s \). Finally, denoting \( b = \frac{B_{ext}}{|B_{ext}|} \) the unit vector aligned with the external magnetic field, we obtain the linearized equation:
\[
\frac{\partial J_s}{\partial t} - \varepsilon_0 \omega_{ps}^2 E - \Omega_{cs} J_s \times b + \nu_s J_s = 0.
\] (7)

The perturbative electromagnetic field \( (E, B) \) satisfies, at order 1 in \( \epsilon \), the usual Maxwell equations derived form (1) and (2), namely the evolution equations:
\[
curl E = -\frac{\partial B}{\partial t}, \quad c^2 \curl B = \frac{J}{\varepsilon_0} + \frac{\partial E}{\partial t}, \quad \text{where:} \quad J := \sum_s J_s,
\]
and the divergence equations:
\[
\div E = \frac{\rho}{\varepsilon_0}, \quad \text{where:} \quad \rho = \sum_s \rho_s, \quad \div B = 0.
\] (8) (9)

Indeed, as its sources are outside the plasma, \( B_{ext}(x) \) is curl- and divergence-free.

For the sake of simplicity, we assume that there only are two species of particles in the plasma: the electrons \( (s = 1) \) and one kind of ions \( (s = 2) \). Obviously, the whole discussion can be extended to an arbitrary number of species, provided they all carry an electric charge (no neutral atoms).

All in all, the model which will be the object of this article is the following. Let \( \Omega \) be a domain in \( \mathbb{R}^3 \), i.e., a bounded, open and connected subset of \( \mathbb{R}^3 \) with a Lipschitz boundary \( \Gamma := \partial \Omega \). The evolution equation for the hydrodynamic and electromagnetic variables are:
\[
\frac{\partial J_1}{\partial t} = \varepsilon_0 \omega_{p1}^2 E + \Omega_{c1} J_1 \times b - \nu_1 J_1, \quad \text{in} \ \Omega \times \mathbb{R}_{>0};
\] (10)
\[
\frac{\partial J_2}{\partial t} = \varepsilon_0 \omega_{p2}^2 E + \Omega_{c2} J_2 \times b - \nu_2 J_2, \quad \text{in} \ \Omega \times \mathbb{R}_{>0};
\] (11)
\[
\frac{\partial E}{\partial t} = c^2 \curl B - \frac{1}{\varepsilon_0} \sum_s J_s, \quad \text{in} \ \Omega \times \mathbb{R}_{>0};
\] (12)
\[
\frac{\partial B}{\partial t} = -\curl E, \quad \text{in} \ \Omega \times \mathbb{R}_{>0};
\] (13)
with the initial conditions at $t = 0$:

$$J_1(0) = J_{1,0}; \ J_2(0) = J_{2,0}; \ E(0) = E_0; \ B(0) = B_0, \text{ in } \Omega.$$  \hspace{1cm} (14)

The boundary $\Gamma$ is split into two parts $\Gamma = \Gamma_A \cup \Gamma_P$, with $\Gamma_A \cap \Gamma_P = \emptyset$; both $\Gamma_P$ and $\Gamma_A$ may be empty. On $\Gamma_P$, there holds a usual perfectly conducting boundary (metallic) condition. On $\Gamma_A$, there holds a Silver–Müller boundary condition:

\[ E \times n = 0, \quad \text{on } \Gamma_P \times \mathbb{R}_{>0}, \]

\[ E \times n + cB_\top = g, \quad \text{on } \Gamma_A \times \mathbb{R}_{>0}, \]  \hspace{1cm} (15) (16)

where $n$ denotes the outward unit normal vector to $\Gamma$, $B_\top$ is the component of $B$ tangent to the boundary $\Gamma$, and $g$ is a data defined on $\Gamma_A \times \mathbb{R}_{>0}$. If $g = 0$, this is an absorbing or outgoing wave condition, meaning that the electromagnetic energy can freely leave the domain through $\Gamma_A$. If $g \neq 0$, this is an incoming wave condition, modelling the injection of an electromagnetic wave into the plasma, and $\Gamma_A$ is interpreted as an antenna (see Fig. 1 for a possible configuration).

The subsets $\Gamma_A$ and $\Gamma_P$ are compact Lipschitz submanifolds of $\Gamma$. When both $\Gamma_P \neq \emptyset$ and $\Gamma_A \neq \emptyset$, we do not necessarily suppose that $\partial \Gamma_A \cap \partial \Gamma_P = \emptyset$ (i.e., we consider both truncated exterior and interior problems), but we do assume that $\Gamma_A$ is not too irregular. A sufficient condition is to assume it either smooth, or polyhedral without so-called pathological vertices [3, p. 204]. This requirement is not very stringent: it can always be satisfied in the outgoing wave case, where $\Gamma_A$ appears as an artificial boundary, whose exact location and shape are to some extent arbitrary.

Otherwise, our assumptions on the domain are minimal. We do not assume $\Omega$ to be topologically trivial (but we do assume that it does not have an infinitely multiple topology), nor $\Gamma$, $\Gamma_A$, $\Gamma_P$ to be connected (though we do assume that they have a finite number of connected components). The perfectly conducting boundary $\Gamma_P$, if not empty, is just assumed to be Lipschitz.

The solution to the system (10)–(13) with boundary conditions (15)–(16) can be shown to satisfy Equation (9) in $\Omega$ for all $t \geq 0$, as well the boundary condition

\[ B \cdot n = 0 \quad \text{on } \Gamma_P \times \mathbb{R}_{>0}, \]  \hspace{1cm} (17)

provided they hold at $t = 0$. These properties will appear crucial for the derivation of the most suitable functional framework for stabilization. Similarly, Equation (8) can be recovered if it holds at $t = 0$ and the charge conservation equation $\partial_t \rho + \text{div} \ J = 0$ is verified; yet, the latter is an immediate consequence of the continuity equations for the various species, viz., $\partial_t \rho_s + \text{div} \ J_s = 0$.

In this article we are interested in to cases: first when $\Gamma_A = \emptyset$, i.e., we have a perfect conductor condition on the whole boundary; the second case when $\Gamma_A$ is non-empty and so Equation (16) holds. In the second case, conditions on and statements about $\Gamma_P$ are of course void if $\Gamma_P = \emptyset$.

As alluded to in §1, the model (10)–(13) has been studied by many authors [18, 19, 25] when the medium is homogeneous and isotropic, i.e., $\Omega_{cs} \equiv 0$, and $\nu_s$ and $\omega_{ps}$ are constants. The dispersive medium model with perfectly conducting boundary condition on the whole boundary has been studied in [18, 25], and it was proven in [18] that it is polynomially stable. In [19], the differential equation (7) is set in a subset of the full domain, and the Silver–Müller boundary condition is imposed on the entire exterior boundary; it was shown that the model is strongly stable. Similarly, some works on the boundary stabilization of the sourceless Maxwell system (v.g., [11, 20]) allow for some inhomogeneity or anisotropy of the permittivity and permeability coefficients, and some works on the internal stabilization by Ohm’s law (v.g., [22]) allow for an inhomogeneous conductivity. But these inhomogeneous or anisotropic terms occur in Maxwell’s equations themselves, not in a coupled ODE as in our model. Furthermore, most of the works which consider mixed boundary conditions actually assume $\partial \Gamma_A \cap \partial \Gamma_P = \emptyset$ (physically, a truncated exterior problem).
Therefore, our goal in the present work is to investigate the stabilization of the model in an inhomogeneous and anisotropic medium with space variable coefficients $\nu_s$, $\omega_{ps}$ and $\Omega_{cs}$, for both types of boundary conditions and both types of truncated problems. We will give sufficient conditions on these coefficients that guarantee first the strong stability, and then the polynomial or exponential stability of the energy.

3. Preliminaries

In this section, we introduce the Hilbert spaces needed in the study of Maxwell’s equations, and the relevant Green’s formulas used in the sequel.

The Sobolev spaces of vector fields $L^2(\Omega) := (L^2(\Omega))^3$, $H^1(\Omega) := (H^1(\Omega))^3$ and $H^\ell(\Gamma) := (H^\ell(\Gamma))^3$, for $\ell \in \{ 1/2, -1/2 \}$ are defined as usual. We denote $(\cdot | \cdot)$ the inner products of both $L^2(\Omega)$ and $L^2(\Omega)$, and $\| \cdot \|$ the associated norm. As usual, $H^1_0(\Omega)$ is the subspace of $H^1(\Omega)$ whose elements vanish on the boundary $\Gamma$. The space $\tilde{H}^{1/2}(\Gamma_A)$ is the subspace of $H^{1/2}(\Gamma_A)$ (the trace space of $H^1(\Omega)$ on $\Gamma_A$) made of fields defined on $\Gamma_A$ such that their extension by zero to $\Gamma_P$ belongs to $H^{1/2}(\Gamma)$. The space $\tilde{H}^{-1/2}(\Gamma_A)$ is the dual space of $\tilde{H}^{1/2}(\Gamma_A)$.

On the other hand, for any Hilbert space $W$ other than $L^2(\Omega)$ or $L^2(\Omega)$, its inner product will be denoted by $(\cdot, \cdot)_W$ and its norm by $\| \cdot \|_W$. The duality pairing between $W$ and its dual space is written as $\langle \cdot, \cdot \rangle_W$; the subscript designates the space to which the second variable belongs.

The spaces $H(\text{div}; \Omega)$ and $H(\text{curl}; \Omega)$ are the usual ones in electromagnetics; they are endowed with their canonical norm. The respective subspaces of fields with vanishing normal (resp. tangential) trace are denoted $H_0(\text{div}; \Omega)$ (resp. $H_0(\text{curl}; \Omega)$). The ranges of the tangential trace mapping $\gamma_T : v \mapsto v \times n$ and the tangential component mapping $\pi : v \mapsto v_T := n \times (v \times n)$ from $H(\text{curl}; \Omega)$ are denoted by

$$
\begin{align*}
TT(\Gamma) & := \{ \varphi \in H^{-1/2}(\Gamma) : \exists v \in H(\text{curl}; \Omega), \; \varphi = v \times n|_{\Gamma} \}, \\
TC(\Gamma) & := \{ \lambda \in H^{1/2}(\Gamma) : \exists v \in H(\text{curl}; \Omega), \; \lambda = v_T|_{\Gamma} \}.
\end{align*}
$$

These two spaces have been described in [7], where they are respectively denote $H^{-1/2}_\parallel(\text{div}_T, \Gamma) = \text{TT}(\Gamma)$ and $H^{-1/2}_\perp(\text{curl}_T, \Gamma) = \text{TC}(\Gamma)$. Furthermore [8], they are in duality with respect to the pivot space

$$L^2_0(\Gamma) := \{ v \in L^2(\Gamma) : v \cdot n = 0 \}.$$

Therefore, one can prove the following formula:

$$
\forall (v, w) \in H(\text{curl}; \Omega)^2, \quad (v \mid \text{curl} \; w) - (\text{curl} \; v \mid w) = \langle v \times n, w_T \rangle_{\text{TC}(\Gamma)}. \tag{18}
$$
The spaces $\mathbf{TT}(\Gamma_A)$ and $\mathbf{TC}(\Gamma_A)$ denote respectively the ranges of $\gamma_T$ and $\pi_T$, restricted on the part $\Gamma_A$ of the boundary. In [7], they are called $\mathbf{H}_{0,\Gamma_0}^{1/2}(\text{div}; \Gamma_A)$ and $\mathbf{H}_{1/2}^{1/2}(\text{curl}; \Gamma_A)$. The subspace of elements of $\mathbf{H}(\text{curl}; \Omega)$ such that the tangential trace vanishes on the part $\Gamma_P$ of the boundary is denoted by

$$\mathbf{H}_{0,\Gamma_P}(\text{curl}; \Omega) = \{ \mathbf{v} \in \mathbf{H}(\text{curl}; \Omega) : \mathbf{v} \times \mathbf{n}|_{\Gamma_P} = 0 \}.$$ 

Then, the range of the trace mappings on $\Gamma_A$ from $\mathbf{H}_{0,\Gamma_P}(\text{curl}; \Omega)$ are denoted

$$\mathbf{TT}(\Gamma_A) := \{ \varphi \in \mathbf{H}^{-1/2}(\Gamma_A) : \exists \mathbf{v} \in \mathbf{H}_{0,\Gamma_P}(\text{curl}; \Omega), \varphi = \mathbf{v} \times \mathbf{n}|_{\Gamma_A} \}$$

$$= \{ \varphi \in \mathbf{TT}(\Gamma_A) : \text{the extension of } \varphi \text{ by } 0 \text{ to } \Gamma \text{ belongs to } \mathbf{TT}(\Gamma) \};$$

$$\mathbf{TC}(\Gamma_A) := \{ \lambda \in \mathbf{H}^{-1/2}(\Gamma_A) : \exists \mathbf{v} \in \mathbf{H}_{0,\Gamma_P}(\text{curl}; \Omega), \lambda = \mathbf{v}|_{\Gamma_A} \}$$

$$= \{ \lambda \in \mathbf{TC}(\Gamma_A) : \text{the extension of } \lambda \text{ by } 0 \text{ to } \Gamma \text{ belongs to } \mathbf{TC}(\Gamma) \};$$

they are respectively called $\mathbf{H}_{1/2}^{1/2}(\text{div}; \Gamma_A)$ and $\mathbf{H}_{1/2}^{1/2}(\text{curl}; \Gamma_A)$ in [7]. The spaces $\mathbf{TT}(\Gamma_A)$ and $\mathbf{TC}(\Gamma_A)$ are in duality with respect to the pivot space $\mathbf{L}^2(\Gamma_A)$, and similarly for $\mathbf{TT}(\Gamma_A)$ and $\mathbf{TC}(\Gamma_A)$. We denote the duality product between those spaces as $\gamma^\lambda_A(\cdot, \cdot)_{\pi_A}$ or $\gamma_A(\cdot, \cdot)_{\pi_A}$. This allows one to derive the following integration by parts formula:

$$\forall (\mathbf{v}, \mathbf{w}) \in \mathbf{H}(\text{curl}; \Omega) \times \mathbf{H}_{0,\Gamma_P}(\text{curl}; \Omega), \quad (\mathbf{v} | \text{curl} \mathbf{w}) - (\text{curl} \mathbf{v} | \mathbf{w}) = \gamma_A(\mathbf{v} \times \mathbf{n}, \mathbf{w} \uparrow)_{\pi_A}. \tag{19}$$

If $\Gamma_P = \emptyset$, i.e., $\Gamma_A = \Gamma$, then $\mathbf{H}_{0,\Gamma_P}(\text{curl}; \Omega) = \mathbf{H}(\text{curl}; \Omega)$, while $\mathbf{TT}(\Gamma_A) = \mathbf{TT}(\Gamma)$ and $\mathbf{TC}(\Gamma_A) = \mathbf{TC}(\Gamma)$. In the case of a truncated exterior problem, i.e., $\partial \Gamma_A \cap \partial \Gamma_P = \emptyset$, it holds again that $\mathbf{TT}(\Gamma_A) = \mathbf{TT}(\Gamma_A)$ and $\mathbf{TC}(\Gamma_A) = \mathbf{TC}(\Gamma_A)$.

A profound and useful property of these spaces is: in the absence of pathological vertices, $\mathbf{TT}(\Gamma_A) \cap \mathbf{TC}(\Gamma_A)$ is included in $\mathbf{L}^2(\Gamma_A)$, see [5] for the truncated exterior problem in a smooth domain and [3, Remarks 5.1.5 and 5.1.8] in the general case. This is the framework of this article.

We shall also use the basic integration by parts formula between $\mathbf{H}(\text{curl}; \Omega)$ and $\mathbf{H}^1(\Omega)$:

$$\forall (\mathbf{v}, \mathbf{w}) \in \mathbf{H}(\text{curl}; \Omega) \times \mathbf{H}^1(\Omega), \quad (\mathbf{v} | \text{curl} \mathbf{w}) - (\text{curl} \mathbf{v} | \mathbf{w}) = \langle \mathbf{v} \times \mathbf{n}, \mathbf{w} \rangle_{\mathbf{H}^{1/2}(\Gamma)} \tag{20}.$$
Hypothesis 1. We suppose that there exists strictly positive real numbers $\nu^s$, $\Omega^*$ and $\omega^*$ such that, for almost all $x \in \Omega$ and for each species $s$ (ions and electrons), one has:

\[
\begin{align*}
0 & \leq \nu_s(x) \leq \nu^*, \\
|\Omega_s(x)| & \leq \Omega^*, \\
0 & < \omega_{ps}(x) \leq \omega^*.
\end{align*}
\]

For $s \in \{1, 2\}$ and $x \in \Omega$ fixed, the mapping $v \mapsto \Omega_{cs}(x) b(x) \times v + \nu_s(x) v$ defined from $\mathbb{R}^3$ (or $\mathbb{C}^3$) to itself is linear. So, there exists a matrix $M \in \mathbb{M}(\mathbb{R})$ such that:

\[
\Omega_{cs}(x) b(x) \times v + \nu_s(x) v = M_s(x)v, \quad \forall v \in \mathbb{R}^3 \text{ or } \mathbb{C}^3.
\]

We denote by $\| \cdot \|_{\mathbb{M}}$ the operator norm on the space $\mathbb{M}_3(\mathbb{C})$ induced by the Hermitian norm of $\mathbb{C}^3$.

Proposition 4.1. There exists $\lambda > 0$ such that $\|\lambda M_s(x)\|_{\mathbb{M}} < 1$, for all $s \in \{1, 2\}$ and $x \in \Omega$. Therefore, the matrix $I + \lambda M_s$ is invertible for all $s \in \{1, 2\}$ and $x \in \Omega$, where $I$ is the identity matrix, and its inverse is uniformly bounded on $\Omega$.

Proof. This is an easy consequence of Hypothesis 1, by a simple perturbation argument. See [16, Propositions 3.1 and 3.2].

Definition 4.2. Let $\lambda$ be given by Proposition 4.1. Let $\mathbb{D}_\lambda : \Omega \rightarrow \mathbb{M}_3(\mathbb{R})$ be the matrix

\[
\mathbb{D}_\lambda(x) := \sum_s \omega_{ps}^2(x)(I + \lambda M_s(x))^{-1}, \quad \text{for } x \in \Omega.
\]

By convention, sums on the variable $s$ run on all particle species, i.e., from $s = 1$ to $2$ in our model.

Proposition 4.3. The matrix $\mathbb{D}_\lambda(x)$ is positive for all $x$ in $\Omega$. Moreover, there exists $\xi > 0$ such that

\[
\sup_{x \in \Omega} \|\mathbb{D}_\lambda(x)\|_{\mathbb{M}} \leq \xi.
\]

Proof. Let $x \in \Omega$. To show the positivity of $\mathbb{D}_\lambda$, it is enough to prove that the matrix $(I + \lambda M_s(x))^{-1}$ is positive for $s \in \{1, 2\}$. Given $v \in \mathbb{R}^3$, we have

\[
(I + \lambda M_s(x))v \cdot v = v \cdot v + \lambda M_s(x)v \cdot v = |v|^2 + \lambda |\nu_s(x)| |v|^2 \geq |v|^2 \geq 0.
\]

Then, $I + \lambda M_s(x)$ is positive. Next, given $w \in \mathbb{R}^3$, there exists $\eta \in \mathbb{R}^3$ such that $w = (I + \lambda M_s(x))\eta$. Hence, it follows that

\[
(I + \lambda M_s(x))^{-1}w \cdot w = \eta \cdot (I + \lambda M_s(x))\eta \geq |\eta|^2 \geq 0.
\]

So, the matrix $(I + \lambda M_s(x))^{-1}$ is positive. The uniform boundedness of $\mathbb{D}_\lambda$ is an easy consequence of Hypothesis 1 and Proposition 4.1.

To prove the well-posedness, we rewrite the system (10)–(14) with boundary condition (15)–(16) as the first order evolution equation

\[
\begin{cases}
\partial_t U + \Lambda U = 0, \\
U(0) = U_0,
\end{cases}
\]

(26)
where the vector $U$ is

$$U = (J_1, J_2, E, B)^\top,$$

and $A$ is a linear operator formally given by the expression

$$A = \begin{pmatrix}
M_1 & 0 & -\varepsilon_0 \omega_{p1}^2 & 0 \\
0 & M_2 & -\varepsilon_0 \omega_{p2}^2 & 0 \\
\frac{1}{\varepsilon_0} & \frac{1}{\varepsilon_0} & 0 & -c^2 \text{curl} \\
0 & 0 & \text{curl} & 0
\end{pmatrix}. \quad (27)$$

The existence and uniqueness of the solution to Problem (26) follows from the classical Lumer–Phillips theorem [9, 21], as we shall see later.

We introduce the weighted $L^2$ spaces associated to each species index $s$:

$$L^2_s(\Omega) := \left\{w : \Omega \to \mathbb{C} \text{ measurable, s.t. } \int_\Omega \frac{|w|^2}{\omega_{ps}} \, d\Omega < +\infty\right\}$$

i.e., $w \in L^2_s(\Omega)$ iff $w/\omega_{ps} \in L^2(\Omega)$, endowed with their canonical norm

$$\|w\|_{(s)} := \|w\|_{L^2_s(\Omega)} := \left\|\frac{w}{\omega_{ps}}\right\|.$$ \quad (28)

In view of the bound (23), one immediately deduces a basic useful result:

**Lemma 4.4.** For each $s$:

(i) The space $L^2_s(\Omega)$ is continuously embedded into $L^2(\Omega)$.

(ii) For any $w \in L^2(\Omega)$, it holds that $\omega_{ps}^2 w \in L^2_s(\Omega)$.

Next, we introduce the energy space

$$X = L^2_1(\Omega) \times L^2_2(\Omega) \times L^2(\Omega) \times L^2(\Omega),$$

and we endow it with the inner product defined for all $U = (U_1, U_2, U_3, U_4)^\top$ and $V = (V_1, V_2, V_3, V_4)^\top$ by

$$(U, V)_X := \frac{1}{\varepsilon_0} \sum_s \left(\frac{U_s}{\omega_{ps}} \left| \frac{V_s}{\omega_{ps}} \right|^2 + \varepsilon_0 (U_3 \mid V_3) + c^2 \varepsilon_0 (U_4 \mid V_4)\right),$$ \quad (30)

and the associated norm $\|\cdot\|_X$.

### 4.1. Perfectly conducting case

Here, we suppose that $\Gamma_A$ is empty. The domain $\Omega$ is encased in a perfect conductor, which means:

$$\forall t > 0, \quad E(t) \times n = 0, \quad B(t) \cdot n = 0, \quad \text{on } \Gamma.$$

Now, we define the linear unbounded operator $\hat{A}_1 : D(\hat{A}_1) \subset X \to X$ as

$$D(\hat{A}_1) := L^2_1(\Omega) \times L^2_2(\Omega) \times H_0(\text{curl}; \Omega) \times H(\text{curl}; \Omega),
\hat{A}_1 U := A U, \quad \forall U \in D(\hat{A}_1). \quad (31)$$

The fact that $\text{im}(\hat{A}_1) \subset X$ follows from Proposition 4.1 and Lemma 4.4. The abstract evolution equation (26) writes:

$$\partial_t U(t) + \hat{A}_1 U(t) = 0, \quad \text{for } t > 0, \quad U(0) = U_0.$$ \quad (32)
Proposition 4.5. The operator $A_1$ is maximal monotone.

Proof. First, we check that $A_1$ is monotone. Given $U = (U_1, U_2, U_3, U_4)^T \in D(A_1)$, one finds, by the definition of $A_1$,

$$ (A_1 U, U)_X = \frac{1}{\varepsilon_0} \sum_s \left( \frac{M_s U_s}{\omega_{ps}} \right) \left( \frac{U_s}{\omega_{ps}} \right) - \sum_s (U_3 | U_s) + \sum_s (U_s | U_3) - \varepsilon_0 c^2 \text{curl} U_4 | U_3 + \varepsilon_0 c^2 (\text{curl} U_3 | U_4). $$

By Lemma 4.4, $U_s \in L^2(\Omega)$ for $s = 1, 2$ too. Taking the real part of this inner product, one gets:

$$ \Re (A_1 U, U)_X = \frac{1}{\varepsilon_0} \sum_s \Re \left( \frac{M_s U_s}{\omega_{ps}} \right) \left( \frac{U_s}{\omega_{ps}} \right) - \varepsilon_0 c^2 \Re [(\text{curl} U_4 | U_3) - (\text{curl} U_3 | U_4)]. \quad (33) $$

But, for all $s = 1, 2$, one has, according to the definition of $M_s$,

$$ \Re \left( \frac{M_s U_s}{\omega_{ps}} \right) \left( \frac{U_s}{\omega_{ps}} \right) = \Re \left( \frac{\nu_s U_s}{\omega_{ps}} \right) \left( \frac{U_s}{\omega_{ps}} \right) + \Re \left( \omega_{cs} \mathbf{b} \times \frac{U_s}{\omega_{ps}} \right) \left( \frac{U_s}{\omega_{ps}} \right) = \left( \frac{\nu_s U_s}{\omega_{ps}} \right) \left( \frac{U_s}{\omega_{ps}} \right). \quad (34) $$

Thus, plugging (34) into (33) and using Green’s formula (18), the boundary condition $U_3 \times n = 0$ on $\Gamma$ and the condition (21), one obtains

$$ \Re (A_1 U, U)_X = \frac{1}{\varepsilon_0} \sum_s \left( \frac{\nu_s U_s}{\omega_{ps}} \right) \left( \frac{U_s}{\omega_{ps}} \right) \geq 0. \quad (35) $$

Hence the monotonicity of $A_1$.

Let us proceed to the maximal character. Let $\lambda > 0$ given by Proposition 4.1. Given any $F = (F_1, F_2, F_3, F_4)^T \in X$, we look for $U = (U_1, U_2, U_3, U_4)^T \in D(A_1)$ such that $(I + \lambda A_1) U = F$. More explicitly, this equation writes:

$$ U_1 + \lambda M_1 U_1 - \lambda \varepsilon_0 \omega_{p1}^2 U_3 = F_1, \quad (36) $$

$$ U_2 + \lambda M_2 U_2 - \lambda \varepsilon_0 \omega_{p2}^2 U_3 = F_2, \quad (37) $$

$$ U_3 + \lambda \varepsilon_0 U_1 + \lambda \varepsilon_0 U_2 - \lambda^2 \text{curl} U_4 = F_3, \quad (38) $$

$$ U_4 + \lambda \text{curl} U_3 = F_4. \quad (39) $$

Assuming that a solution $U$ of (36)–(39) exists, we can eliminate the equations (36), (37) and (39) respectively:

$$ U_1 = (I + \lambda M_1)^{-1} (F_1 + \lambda \varepsilon_0 \omega_{p1}^2 U_3), \quad (40) $$

$$ U_2 = (I + \lambda M_2)^{-1} (F_2 + \lambda \varepsilon_0 \omega_{p2}^2 U_3), \quad (41) $$

$$ U_4 = F_4 - \lambda \text{curl} U_3. \quad (42) $$

Inserting these three expressions into (38), one obtains, in function of $U_3$,

$$ U_3 + \lambda^2 c^2 \text{curl} \text{curl} U_3 + \lambda^2 \varepsilon_0 \lambda U_3 = F_3 + \lambda c^2 \text{curl} F_4 - \frac{\lambda}{\varepsilon_0} \sum_s (I + \lambda M_s)^{-1} F_s. \quad (43) $$

Multiplying this identity by a test-function $v \in H_0(\text{curl}; \Omega)$ and applying the Green formula (18), one finds the following variational formulation:
Find $U_3 \in H_0(\text{curl}; \Omega)$ such that

$$a(U_3, v) = L(v), \quad \forall v \in H_0(\text{curl}; \Omega)$$

(44)

where the forms $a$ and $L$ are defined on $H(\text{curl}; \Omega)$ as:

$$a(w, v) := (w | v) + \lambda^2 c^2 (\text{curl} w | \text{curl} v) + \lambda^2 (D_\lambda w | v),$$

$$L(v) := (F_3 | v) + \lambda c^2 (F_4 | \text{curl} v) - \frac{\lambda}{\varepsilon_0} \sum_s ((I + \lambda M_s)^{-1} F_s | v).$$

(45)

(46)

The problem (44) is well-posed. Indeed, thanks to Proposition 4.3, the sesquilinear form $a$ is continuous and coercive on $H_0(\text{curl}; \Omega)$. The form $L$ is anti-linear, and by Proposition 4.1 and Lemma 4.4, it obviously continuous on $H_0(\text{curl}; \Omega)$. Then, we conclude by the Lax–Milgram theorem the existence of a unique solution $U_3 \in H_0(\text{curl}; \Omega)$ to the formulation (44).

Returning to the problem (36)–(39), we define $U_1$ and $U_2$ by (40) and (41). Again, by Proposition 4.1 and Lemma 4.4, they respectively belong to $L^2(1)(\Omega)$ and $L^2(2)(\Omega)$. Also, we define $U_4$ by (42); it belongs to $L^2(\Omega)$. Next, if we take $v \in D(\Omega)$ as a test function in the formulation (44) and use the Green formula (18), we obtain Equation (43). So, by the definition of $U_4$, we can write this equation as

$$U_3 - \lambda c^2 \text{curl} U_4 + \lambda^2 \Delta_\lambda U_3 = F_3 - \frac{\lambda}{\varepsilon_0} \sum_s (I + \lambda M_s)^{-1} F_s.$$  

(47)

This equation, on the one hand, implies that $\text{curl} U_4 \in L^2(\Omega)$, and on the other hand is equivalent to (38) (just replace $\Delta_\lambda$ with its expression). Hence, the quadruple $(U_1, U_2, U_3, U_4)$ belongs to $D(\mathcal{A}_1)$ and it solves the equations (36)–(39). The proof is completed.

**Theorem 4.6.** The operator $-\mathcal{A}_1$ generates a $C^0$-semigroup of contractions $(T_1(t))_{t \geq 0}$ on the energy space $X$. Thus, for all $U_0 \in X$, there exists a unique solution $U \in C^0(\mathbb{R}_{\geq 0}; X)$, given by $U(t) = T_1(t) U_0$, which solves the problem (32).

Moreover, if $U_0 \in D(\mathcal{A}_1)$, then

$$U \in C^1(\mathbb{R}_{\geq 0}; X) \cap C^0(\mathbb{R}_{\geq 0}; D(\mathcal{A}_1)).$$

Furthermore, we have $\|U(t)\|_X \leq \|U_0\|_X$ and $\|\partial_t U(t)\|_X \leq \|\mathcal{A}_1 U_0\|_X$.

**Proof.** From the previous proposition, the operator $-\mathcal{A}_1$ is maximal dissipative. The domain $D(\mathcal{A}_1)$ of $-\mathcal{A}_1$ is dense in $X$ according to [21, Theorem 1.4.6]. Then, we can apply the Lumer–Phillips theorem (see [21, Theorem 1.4.3]) to obtain the result.

**4.2. Silver–Müller case**

Now, we assume that $\Gamma_A$ is non-empty. A Silver–Müller boundary condition holds on the antenna $\Gamma_A$, and a perfect conductor boundary condition on the rest of the boundary $\Gamma_P$:

$$\begin{align*}
E(t) \times n &= 0 \quad \text{on} \ \Gamma_P, \ t > 0, \\
E(t) \times n + cB_\top(t) &= g(t) \quad \text{on} \ \Gamma_A, \ t > 0.
\end{align*}$$

(48)

Our goal is to solve Problem (26) with the boundary condition (48). First, we will start with the homogeneous (or absorbing, outgoing wave) case, $g = 0$, and next we proceed to the general (incoming wave) case, i.e., $g \neq 0$. 
4.2.1. Homogeneous (absorbing) boundary condition

Let us define the linear unbounded operator \( \mathbb{A}_2 : D(\mathbb{A}_2) \subset X \to X \) as

\[
D(\mathbb{A}_2) := L^2_{(1)}(\Omega) \times L^2_{(2)}(\Omega) \times \mathcal{H},
\]

where

\[
\mathcal{H} = \{(V_3, V_4) \in H_{0, \Gamma_p}(\text{curl}; \Omega) \times \mathbf{H}(\text{curl}; \Omega) : V_3 \times n + c V_4 = 0 \text{ on } \Gamma_A\},
\]

and

\[
\mathbb{A}_2 U := \mathbb{A} U, \quad \forall U \in D(\mathbb{A}_2).
\] (49)

Therefore, the abstract evolution equation (26) writes:

\[
\partial_t U(t) + \mathbb{A}_2 U(t) = 0, \quad \text{for } t > 0, \quad U(0) = U_0.
\] (50)

We shall need the following Hilbert space

\[
\mathcal{V} := \{v \in H_{0, \Gamma_p}(\text{curl}; \Omega) : v_T \in L^2(\Gamma_A)\}
\]

equipped with the inner product

\[
(w, v)_\mathcal{V} := (w | v) + (\text{curl } w | \text{curl } v) + (w_T | v_T)_{\Gamma_A}.
\] (52)

Above, \((\cdot | \cdot)_{\Gamma_A}\) denotes the inner product in \(L^2(\Gamma_A)\).

**Proposition 4.7.** The operator \( \mathbb{A}_2 \) is maximal monotone.

**Proof.** Let us start by proving the monotonicity of \( \mathbb{A}_2 \). Pick any \( U = (U_1, U_2, U_3, U_4)^\top \in D(\mathbb{A}_2) \). The equality (33) still holds; it only relies on the expression of \( \mathbb{A} \) in \( \Omega \), not on the boundary conditions. As \( U_3 \in H_{0, \Gamma_p}(\text{curl}; \Omega) \), we get by the integration-by-parts formula (19):

\[
\Re[(\text{curl } U_4 | U_3) - (\text{curl } U_3 | U_4)] = \Re(\langle \lambda \mathbb{A}_2 \mathbf{X} \times n, U_3 \mathbf{X} \times n \rangle_{\pi_A}).
\]

Now, we use the Silver–Müller boundary condition \( U_3 \times n + c U_4 = 0 \) on \( \Gamma_A \). We remark that both \( U_3 \times n \) and \( U_4 = 0 \) belong to \( \mathcal{T}(\Gamma_A) \cap \mathcal{C}(\Gamma_A) \subset L^2(\Gamma_A) \) as said in §3. Then, it holds that

\[
\Re(\langle \lambda \mathbb{A}_2 \mathbf{X} \times n, U_3 \mathbf{X} \times n \rangle_{\pi_A}) = -c \| U_4 \|^2_{L^2(\Gamma_A)}.
\]

We thus conclude from (33) that

\[
\Re(\mathbb{A}_2 U, U) = \frac{1}{\varepsilon_0} \sum_s \left( \frac{\nu_s U_s}{\omega ps} \right) \frac{U_s}{\omega ps} + \varepsilon_0 c^2 \| U_4 \|^2_{L^2(\Gamma_A)} \geq 0
\] (53)

which yields the monotonicity of the operator \( \mathbb{A}_2 \).

Now we show the maximality of \( \mathbb{A}_2 \). Again, we use the same \( \lambda > 0 \) given by Proposition 4.1. Given any \( F = (F_1, F_2, F_3, F_4)^\top \in X \), we look for \( U = (U_1, U_2, U_3, U_4)^\top \in D(\mathbb{A}_2) \) such that \( (I + \lambda \mathbb{A}_2) U = F \), which is equivalent to the system (36)–(39) (plus boundary conditions). Following the same argument as in Proposition 4.5, we can eliminate \( U_1, U_2 \) and \( U_4 \), and they are given respectively by (40), (41) and (42), while \( U_3 \) verifies the equation:

\[
U_3 + \lambda^2 c^2 \text{curl curl } U_3 + \lambda^2 \mathbb{A}_2 U_3 = F_3 + \lambda c^2 \text{curl } F_4 - \frac{\lambda}{\varepsilon_0} \sum_s (I + \lambda \mathbb{M}_s)^{-1} F_s.
\] (54)
Thus, multiplying (54) by a test-function \( \mathbf{v} \in \mathcal{V} \), applying Green’s formula (19), and using the Silver–Müller boundary condition and the expression (42), we arrive at the variational formulation:

*Find \( U_3 \in \mathcal{V} \) such that*

\[
\tilde{a}(U_3, \mathbf{v}) = L(\mathbf{v}), \quad \forall \mathbf{v} \in \mathcal{V}
\]  

(55)

with the sesquilinear form \( \tilde{a} \) defined as:

\[
\tilde{a}(\mathbf{w}, \mathbf{v}) := a(\mathbf{w}, \mathbf{v}) + \lambda c (\mathbf{w}^T | \mathbf{v}^T)_{\Gamma_A},
\]  

(56)

and the forms \( a \) and \( L \) given respectively by (45) and (46).

As the form \( a \) is coercive on \( H(\text{curl}; \Omega) \) (Proposition 4.5), the form \( \tilde{a} \) is coercive on \( \mathcal{V} \). So, by Lax–Miilgram theorem, Problem (55) admits a unique solution \( U_3 \in \mathcal{V} \). Defining \( U_1, U_2 \) and \( U_4 \) respectively by (40), (41) and (42), they respectively belong to \( L^2(\Omega) \), \( L^2(\Omega) \) and \( L^2(\Omega) \); taking a test-function \( \mathbf{v} \in D(\Omega) \) in (55), we find the equation (54) which is equivalent to (38). Thus \( U = (U_1, U_2, U_3, U_4) \) formally satisfies (I + \( \lambda A_2 \)) \( \mathbf{U} = \mathbf{F} \), and in order to prove that \( D(A_2) \) it remains only to check the homogeneous Silver–Müller boundary condition on \( \Gamma_A \). To this end, using the integration-by-parts formula (19) in (55) and the definition of \( U_4 \), it follows from the identity (54) that:

\[
\lambda c (U_3^T | \mathbf{v}^T)_{\Gamma_A} - \lambda c^2 (U_4 \times \mathbf{n}, \mathbf{v})_{\gamma_A} = 0, \quad \forall \mathbf{v} \in \mathcal{V}.
\]  

(57)

Let \( \omega \in \overline{H}^\frac{3}{2}(\Gamma_A) \) and \( \overline{\omega} \in \overline{H}^\frac{1}{2}(\Gamma) \) be its extension by 0 to the whole boundary. By the surjectivity of the trace mapping, there exists \( \mathbf{v} \in \overline{H}^1(\Omega) \) such that \( \overline{\omega} = \mathbf{v}|_\Gamma \); clearly, \( \mathbf{v} \in \mathcal{V} \). From the integration by parts formulas (19), (20) applied to \( U_4 \) and \( \mathbf{v} \), we get that

\[
\gamma_A (U_4 \times \mathbf{n}, \mathbf{v})_{\gamma_A} = (U_4 \times \mathbf{n}, \mathbf{v})_{\overline{H}^\frac{1}{2}(\Gamma_A)}.
\]  

(58)

Recalling that \( \mathbf{v}|_\Gamma = \mathbf{v}^T + (\mathbf{n} \cdot \mathbf{v}) \mathbf{n} \), it follows that \( (U_3^T | \mathbf{v}^T)_{\Gamma_A} = (U_3^T | \mathbf{v})_{\Gamma_A} \). Using (58) and the previous identity, Equation (57) becomes:

\[
(U_3^T | \mathbf{v})_{\Gamma_A} - c (U_4 \times \mathbf{n}, \mathbf{v})_{\overline{H}^\frac{1}{2}(\Gamma_A)} = 0.
\]  

(59)

As \( \mathbf{v}|_{\Gamma_A} = \omega \) and \( \mathbf{w} \) is arbitrary in \( \overline{H}^\frac{3}{2}(\Gamma_A) \), one concludes from (59) that \( U_3^T - c U_4 \times \mathbf{n} = 0 \) in \( \overline{H}^{\frac{1}{2}}(\Gamma_A) \) which is equivalent to \( U_3 \times \mathbf{n} + c U_4^T = 0 \) in \( \overline{H}^{\frac{1}{2}}(\Gamma_A) \), and therefore also in \( L^2(\Gamma_A) \) because \( U_3^T \) is in \( L^2(\Gamma_A) \) (plus a density argument). This proves the Silver–Müller boundary condition, and the proof of the Proposition is complete.

\[\blacksquare\]

**Theorem 4.8.** The operator \( -A_2 \) generates a \( C^0 \)-semigroup of contractions \( (T_2(t))_{t \geq 0} \) on the energy space \( \mathbf{X} \). Thus, for all \( \mathbf{U}_0 \in \mathbf{X} \), there exists a unique solution \( \mathbf{U} \in C^0(\mathbb{R}_{\geq 0}; \mathbf{X}) \), given by \( \mathbf{U}(t) = T_2(t) \mathbf{U}_0 \), which solves the problem (50).

Moreover, if \( \mathbf{U}_0 \in D(A_2) \), then

\[
\mathbf{U} \in C^1(\mathbb{R}_{\geq 0}; \mathbf{X}) \cap C^0(\mathbb{R}_{\geq 0}; D(A_2)).
\]

Furthermore, we have \( \| \mathbf{U}(t) \|_\mathbf{X} \leq \| \mathbf{U}_0 \|_\mathbf{X} \) and \( \| \partial_t \mathbf{U}(t) \|_\mathbf{X} \leq \| A_2 \mathbf{U}_0 \|_\mathbf{X} \).

**Proof.** Entirely similar to Theorem 4.6. \[\blacksquare\]
4.2.2. General (non-homogeneous) boundary condition

Here, we suppose that \( g \neq 0 \) in (48). We shall solve the evolution problem by using a lifting of the boundary data \( g \). To this end, we introduce the mapping:

\[
Z_A : \mathbf{H}_{0, \Gamma_p}(\text{curl}; \Omega) \times \mathbf{H}(\text{curl}; \Omega) \to \mathbf{\tilde{T}}(\Gamma_A) + \mathbf{TC}(\Gamma_A)
\]

\[
(v, w) \mapsto \gamma_T(v) + \pi_T(w).
\]

It is clear that \( Z_A \) is linear and continuous, and due to the surjectivity of \( \gamma_T \) and \( \pi_T \) (see the definition of \( \mathbf{\tilde{T}} \) and \( \mathbf{TC} \)), \( Z_A \) is also surjective. Then, we deduce that \( Z_A \) is bijective from \( \ker Z_A \) to \( \mathbf{\tilde{T}}(\Gamma_A) + \mathbf{TC}(\Gamma_A) \) and we denote its inverse by \( R_A \). By the Banach–Schauder theorem, \( R_A \) is continuous.

We assume the following regularity on the boundary data \( g \):

\[
g \in W^{2,1}(\mathbb{R}_{>0}; \mathbf{\tilde{T}}(\Gamma_A) + \mathbf{TC}(\Gamma_A)). \tag{60}
\]

According to the previous paragraph, for any \( t \geq 0 \) there exists \( (g_3(t), g_4(t)) \in \mathbf{H}_{0, \Gamma_p}(\text{curl}; \Omega) \times \mathbf{H}(\text{curl}; \Omega) \) such that

\[
(g_3(t), g_4(t)) = R_A[g(t)], \quad \text{i.e.,} \quad g_3(t) \times n + c g_4 T(t) = g(t) \text{ on } \Gamma_A,
\]

and the functions \( (g_3, g_4) \) have the following regularity:

\[
(g_3, g_4) \in W^{2,1}(\mathbb{R}_{>0}; \mathbf{H}_{0, \Gamma_p}(\text{curl}; \Omega) \times \mathbf{H}(\text{curl}; \Omega)). \tag{62}
\]

**Theorem 4.9.** Suppose that the initial data satisfy:

\[
\begin{cases}
J_{1,0} \in L^2(1)(\Omega), & J_{2,0} \in L^2(2)(\Omega), \\
E_0 \in \mathbf{H}_{0, \Gamma_p}(\text{curl}; \Omega), & B_0 \in \mathbf{H}(\text{curl}; \Omega), \\
E_0 \times n + c B_0 T = g(0) \text{ on } \Gamma_A,
\end{cases} \tag{63}
\]

and \( g \) is of regularity (60), which gives a meaning to the initial value \( g(0) \). Then, there exists one, and only one, solution \( U = (J_1, J_2, E, B)^\top \) to the evolution problem (26), supplemented with the boundary conditions (48), such that its components have the following regularity:

\[
\begin{align*}
(J_1, J_2) & \in C^1(\mathbb{R}_{>0}; L^2(1)(\Omega) \times L^2(2)(\Omega)), \\
E & \in C^1(\mathbb{R}_{>0}; L^2(\Omega)) \cap C^0(\mathbb{R}_{>0}; \mathbf{H}_{0, \Gamma_p}(\text{curl}; \Omega)), \\
B & \in C^1(\mathbb{R}_{>0}; L^2(\Omega)) \cap C^0(\mathbb{R}_{>0}; \mathbf{H}(\text{curl}; \Omega)).
\end{align*}
\]

**Proof.** Define \( (g_3, g_4) \) by (61), and introduce the auxiliary unknown \( U^* = (J_1^*, J_2^*, E^*, B^*)^\top \):

\[
J_1^* = J_1, \quad J_2^* = J_2, \quad E^* = E - g_3, \quad B^* = B - g_4.
\]

If a solution \( (J_1, J_2, E, B)^\top \) as above exists then, by construction, the field \( U^*(t) \) belongs to \( D(A_2) \) for any \( t \geq 0 \). Moreover it is governed by the evolution equations

\[
\begin{align*}
\partial_t U^* + \mathbf{A} U^* &= \mathbf{F}, & t > 0, \\
U^*(0) &= U_0^*.
\end{align*}
\]

(64) \hspace{1cm} (65)
with data

\[
F = \begin{pmatrix}
\varepsilon_0 \omega_0^2 g_3 \\
\varepsilon_0 \omega_0^2 g_3 \\
-\partial_t g_3 + c^2 \text{curl} g_3 \\
-\partial_t g_4 - \text{curl} g_3
\end{pmatrix}, \quad U_0^* = \begin{pmatrix}
J_{1,0}
J_{2,0}
E_0 - g_3(0)
B_0 - g_4(0)
\end{pmatrix}.
\]

Thanks to (62) and Lemma 4.4, one sees that \( F \in W^{1,1}(\mathbb{R}_0; X) \); and, obviously, \( U_0^* \in D(A_2) \). Thus, Problem (64)–(65) admits a unique strong solution [9, Proposition 4.1.6], with regularity \( U^* \in C^1(\mathbb{R}_0; X) \cap C^0(\mathbb{R}_0; D(A_2)) \), which depends continuously on the data \( F \) and \( U_0^* \). Hence, we conclude the existence of

\[
U = (J_1, J_2, E, B)^\top = (J_1^*, J_2^*, E^* + g_3, B^* + g_4)^\top
\]
solution to (26) with boundary condition (48), and depending continuously on the data \( g \) and \( U_0 \). To get uniqueness, we notice that the difference of two solutions solves the homogeneous problem (50) with zero initial data, so it vanishes. \( \square \)

4.3. On the constraint equations

Following the usual pattern in electromagnetics, the constraints on the fields: divergence equations (8), (9), magnetic boundary condition (17), are preserved by the evolution semigroup, provided the sources \((\rho, J) := \sum_s (\rho_s, J_s)\) satisfy the charge conservation equation. We omit the proofs, as they are extremely classical [3, Remark 5.1.2, Thms 5.2.3 and 5.2.12]. The details can be found in [16, §4]. As a matter of fact, once the existence and uniqueness of the solution to the coupled model is obtained, the electromagnetic variables \((E, B)\) naturally appear as the solution to the Maxwell equations with data \((\rho, J)\).

**Theorem 4.10.** Assume that

\[
\text{div } E_0 = \frac{\rho(0)}{\varepsilon_0}, \quad \text{and} \quad \text{div } B_0 = 0 \quad \text{in } \Omega, \quad B_0 \cdot n = 0 \quad \text{on } \Gamma_P,
\]

and that the charge conservation equation

\[
\frac{\partial \rho(t)}{\partial t} + \text{div } J(t) = 0 \quad \text{holds in } \Omega \text{ for a.e. } t > 0.
\]

Then, for all \( t > 0 \), the electric field \( E \) satisfies (8) and the magnetic field \( B \) satisfies (9) and (17).

**Remark 4.11.** For \( \ell = 1, 2 \), we define \( X_\ell := L^2_{(1)}(\Omega) \times L^2_{(2)}(\Omega) \times L^2(\Omega) \times H_{0,\Gamma_P}(\text{div } 0; \Omega) \) where the case \( \ell = 1 \) corresponds to \( \Gamma_A = \emptyset \), i.e., \( \Gamma_P = \Gamma \) and \( \ell = 2 \) is for the case \( \Gamma_A \neq \emptyset \). Then, \( \text{im } (A_\ell) \subset X_\ell \) and, according to Theorem 4.10, we conclude that the space \( X_\ell \) is stable by the semigroup \( T_\ell \) generated by the operator \(-A_\ell\), i.e.,

- For all \( U_0 \in D(A_1) \cap X_1 \), there exists a unique \( U \in C^1(\mathbb{R}_0; X_1) \cap C^0(\mathbb{R}_0; D(A_1) \cap X_1) \) solution to the system of equations (10)–(14) and (9) with boundary conditions (15) and (17).
- For all \( U_0 \in D(A_2) \cap X_2 \), there exists a unique \( U \in C^1(\mathbb{R}_0; X_2) \cap C^0(\mathbb{R}_0; D(A_2) \cap X_2) \) solution to the system of equations (10)–(14) and (9) with boundary conditions (15)–(17).

Also, for all \( \ell \), if we take \( U_0 \in X_\ell \), the two problems above have a weak solution \( U \in C^0(\mathbb{R}_0; X_\ell) \).
Figure 2. Example of non-topologically trivial domain with a non-connected boundary. The domain $\Omega$ is made of the interior of the torus minus the green cylinders. The boundary $\partial \Omega$ is the union of the boundary of the torus and the cylinders which are all disjoint. The purple surface is a cut $\Sigma_1$, and the set $\hat{\Omega} = \Omega \setminus \Sigma_1$ is simply connected.

5. Some results of functional analysis

5.1. The geometry

As said in §2, the domain $\Omega$ can be topologically non-trivial, and the boundary $\Gamma$ can be connected, or not; see Figure 2 for an example. We now introduce some notations associated with this geometry; we use the notations from [1,3,12].

We denote by $\Gamma_k$, $0 \leq k \leq K$ the connected components of $\Gamma$, $\Gamma_0$ being the boundary of the unbounded component of $\mathbb{R}^3 \setminus \overline{\Omega}$. When the boundary is connected, $\Gamma_0 = \Gamma$. Let us introduce a subspace of $H^1(\Omega)$:

$$H^1_{\partial \Omega}(\Omega) := \{ q \in H^1(\Omega) : q|_{\Gamma_0} = 0, q|_{\Gamma_k} = C_k, 1 \leq k \leq K \}.$$  

Above, $C_k$ means a constant, and for $\ell \neq k$, $C_\ell$ and $C_k$ may be different. This space can be endowed with the norm $\| \cdot \|_{H^1_{\partial \Omega}(\Omega)} = \| \text{grad} \cdot \|$ (see [3, Proposition 2.1.66]).

We assume that there exist $J$ connected open surfaces $\Sigma_j$, $j = 1, \ldots, J$, called “cuts”, contained in $\Omega$, such that:

i) each surface $\Sigma_j$ is a smooth, orientable two-dimensional manifold;

ii) the boundary of $\Sigma_j$ is contained in $\partial \Omega$;

iii) the intersection $\Sigma_j \cap \Sigma_i$ is empty for $i \neq j$;

iv) (if $\Gamma_A \neq \emptyset$) $\Gamma_A \setminus \partial \Sigma$, where $\Sigma = \bigcup_{j=1}^J \Sigma_j$, has a finite number of connected components, denoted $\Gamma_{A,i}$, $i = 1, \ldots, N$, whose closures are compact Lipschitz submanifolds of $\Gamma$;

v) the open set $\hat{\Omega} := \Omega \setminus \Sigma$ is pseudo-Lipschitz [1, Definition 3.1] and topologically trivial (i.e., any vector field with vanishing curl is the gradient of a scalar field on $\hat{\Omega}$).

If $\Omega$ is topologically trivial, $J = 0$ and $\hat{\Omega} = \hat{\Omega}$. The extension operator from $L^2(\hat{\Omega})$ to $L^2(\Omega)$ is denoted $\tilde{\cdot}$, whereas $[\cdot]_{\Sigma_j}$ denotes the jump across the surface $\Sigma_j$, $j = 1, \ldots, J$. Being orientable, each cut is assumed to have a “plus” and a “minus” side, so $[w]_{\Sigma_j} = w_{|_{\Sigma_j^+}} - w_{|_{\Sigma_j^-}}$. For all $j$, we denote $\langle \cdot, \cdot \rangle_{\Sigma_j}$ the duality pairing between $H^{1/2}(\Sigma_j)$ and its dual $H^{-1/2}(\Sigma_j)$.  

5.2. Hodge decompositions and topology-related spaces

Let \( \mathbb{B} : \Omega \rightarrow \mathcal{M}_3(\mathbb{C}) \) be a matrix-valued function. We make the following assumption:

\[
\exists \eta, \zeta > 0, \quad \eta(v^* v) \geq \|v^* \mathbb{B}(x)v\| \geq \zeta(v^* v), \quad \forall v \in \mathcal{C}^1, \quad \forall x \in \Omega. \tag{66}
\]

Define the Hilbert space

\[
\mathbf{H}(\text{div } \mathbb{B}; \Omega) := \{ v \in \mathbf{L}^2(\Omega) : \text{div } \mathbb{B}v \in \mathbf{L}^2(\Omega) \}.
\]

This space is equipped with the canonical norm \( v \mapsto (\|v\|^2 + \|\text{div } \mathbb{B}v\|^2)^{1/2} \). The subspace \( \mathbf{H}(\text{div } \mathbb{B}0; \Omega) := \{ v \in \mathbf{L}^2(\Omega) : \text{div } \mathbb{B}v = 0 \} \) is obviously a closed subspace of both \( \mathbf{H}(\text{div } \mathbb{B}; \Omega) \) and \( \mathbf{L}^2(\Omega) \). If \( v \in \mathbf{H}(\text{div } \mathbb{B}; \Omega) \), the normal trace of \( v \) is a well-defined element of \( \mathbf{H}^{1/2}(\Gamma) \) and the integration by parts formula holds

\[
\forall v \in \mathbf{H}(\text{div } \mathbb{B}; \Omega), \forall q \in \mathbf{H}^1(\Omega), \quad (\mathbb{B}v | \text{grad } q) + (\text{div } \mathbb{B}v | q) = (\mathbb{B}v \cdot n, q)_{\mathbf{H}^{1/2}(\Gamma)}.
\]

If \( q \in \mathbf{H}_{0}^1(\Omega) \), the above formula can be extended to \( v \in \mathbf{L}^2(\Omega) \). Then, \( \text{div } \mathbb{B}v \in \mathbf{H}^{-1}(\Omega) \) and one gets

\[
(\mathbb{B}v | \text{grad } q) + (\text{div } \mathbb{B}v, q)_{\mathbf{H}_{0}^1(\Omega)} = 0. \tag{68}
\]

In this paragraph, we introduce some other spaces and notations associated to a matrix \( \mathbb{B} \) satisfying (66), and we prove some useful results. We start with a result on elliptic problems, whose proof is straightforward and left to the reader.

**Lemma 5.1.** For any \( f \in \mathbf{H}^{-1}(\Omega) \), the elliptic problem:

\[
\begin{aligned}
&\text{Find } q \in \mathbf{H}_{0}^1(\Omega) \text{ such that} \\
&-\Delta q := -\text{div}(\mathbb{B} \text{grad } q) = f
\end{aligned}
\]

admits a unique solution. Furthermore, there exists a constant \( C > 0 \) such that

\[
\|q\|_{\mathbf{H}^1(\Omega)} \leq C \|f\|_{\mathbf{H}^{-1}(\Omega)}. \tag{70}
\]

**Lemma 5.2.** For any \( v \in \mathbf{L}^2(\Omega) \), there exists a unique pair \( (q, v^T) \in \mathbf{H}_{0}^1(\Omega) \times \mathbf{L}^2(\Omega) \) satisfying the conditions

\[
v = \text{grad } q + v^T, \quad \text{div } (\mathbb{B}v^T) = 0. \tag{71}
\]

Moreover, there exists \( C > 0 \) independent constant of \( v \) such that

\[
\|\text{grad } q\| \leq C \|v\|, \quad \|v^T\| \leq C \|v\|. \tag{72}
\]

**Proof.** Let \( v \in \mathbf{L}^2(\Omega) \). As \( \mathbb{B} \) is bounded and the application \( \text{div} \) is continuous from \( \mathbf{L}^2(\Omega) \) to \( \mathbf{H}^{-1}(\Omega) \), we have \( \text{div } \mathbb{B}v \in \mathbf{H}^{-1}(\Omega) \) and \( \|\text{div } \mathbb{B}v\|_{\mathbf{H}^{-1}(\Omega)} \leq C_1 \|v\| \). According to Lemma 5.1, there exists one, and only one, \( q \in \mathbf{H}_{0}^1(\Omega) \) that solves the problem (69) with data \( f = -\text{div } \mathbb{B}v \) and satisfies \( \|\text{grad } q\| \leq C \|\text{div } \mathbb{B}v\|_{\mathbf{H}^{-1}(\Omega)} \). Finally, let \( v^T = v - \text{grad } q \). By construction, we have \( v^T \in \mathbf{L}^2(\Omega) \) and \( \text{div } \mathbb{B}v^T = 0 \). The estimates of (72) are also established. 

We now characterize the following space:

\[
Z_N(\Omega; \mathbb{B}) := \mathbf{H}_{0}(\text{curl } 0; \Omega) \cap \mathbf{H}(\text{div } 0; \Omega).
\]
**Proposition 5.3.** The dimension of the vector space $Z_N(\Omega; B)$ is equal to $K$, the number of connected components of the boundary, minus one. Furthermore, a basis of $Z_N(\Omega; B)$ is the set of the functions $(\text{grad} \ q_k)_{1 \leq k \leq K}$, where each $q_k$ is the unique solution in $H^1(\Omega)$ to the problem

\[
\begin{cases}
\Delta_B q_k = \text{div} B \text{grad} q_k = 0, & \text{in } \Omega, \\
q_k|_{\Gamma_o} = 0 \quad \text{and} \quad q_k|_{\Gamma_i} = \text{cst}, & 1 \leq i \leq K, \\
(\mathbb{B} \text{grad} q_k \cdot n)_{H^\frac{1}{2}(\Gamma_i)} = -1 & \text{and} \quad (\mathbb{B} \text{grad} q_k \cdot n, 1)_{H^\frac{1}{2}(\Gamma_i)} = \delta_{ki}, \ 1 \leq i \leq K.
\end{cases}
\] (73)

**Proof.** Entirely similar to [1, Proposition 3.18], using the integration-by-parts formulas (68) and (67), and the well-posedness of elliptic problems involving the operator $\Delta_B$, as in Lemma 5.1. \qed

**Remark 5.4.** All norms being equivalent on the finite-dimensional space $Z_N(\Omega; B)$, we may use any norm to measure elements of this space; for example

\[ v \mapsto \|v\|, \quad \text{or} \quad v \mapsto \|(\mathbb{B}v \cdot n, 1)_{H^\frac{1}{2}(\Gamma_i)}\|_{1 \leq i \leq K}, \]

with $1 \leq p \leq \infty$. Also, we easily check that $Z_N(\Omega; B) = \text{grad}[Q_N(\Omega; B)]$, where

\[ Q_N(\Omega; B) := \{ q \in H^\frac{1}{2}(\partial \Omega) : \text{div} B \text{grad} q = 0 \text{ in } \Omega \}, \]

so, $v = \text{grad} q \mapsto (q|_{\Gamma_i})_{1 \leq i \leq K}$, with $1 \leq p \leq \infty$, is another norm. Hereafter, we denote $\|\cdot\|_{Z_N(\Omega; B)}$ the chosen norm.

### 5.3. A compactness result

We introduce the function space

\[ X_{N,\Gamma}(\Omega; B) := \{ w \in H(\text{curl}; \Omega) : \text{div} B w \in L^2(\Omega) \text{ and } w \times n_{\Gamma} \in L^2(\Gamma) \}; \]

obviously, $w \times n_{\Gamma}$ can be replaced with $w_{\Gamma|\Gamma}$ in the above definition. It is endowed with its canonical norm

\[ \|w\|_{X_{N,\Gamma}(\Omega; B)}^2 = \|w\|^2 + \|\text{curl} w\|^2 + \|\text{div} B w\|^2 + \|w_{\Gamma}\|^2_{L^2(\Gamma)}. \] (74)

Below, we derive some useful properties of the space $X_{N,\Gamma}(\Omega; B)$: it is compactly embedded into $L^2(\Omega)$, which yields an inequality in $L^2$ norm for elements of $X_{N,\Gamma}(\Omega; B)$, and finally a new norm equivalent to (74). These results parallel and generalize those of [13, Thm 3.22] (for the boundary condition $w \times n = 0$ and $\Gamma$ connected) and [3, Thm 8.1.3] (where $B$ is assumed to be real and symmetric, and $w \times n = 0$ on $\Gamma_P$), both of which grounded in the pioneering work [26, Theorem 2.2]. However, we choose to present the proof, as the two simultaneous negative features (non-Hermitianness of $B$ and non-connectedness of $\Gamma$) call for a careful demonstration.

#### 5.3.1. Compact embedding of $X_{N,\Gamma}(\Omega; B)$ into $L^2(\Omega)$

We denote

\[ Z_N(\Omega) := H_0(\text{curl}; \Omega) \cap H(\text{div}; \Omega) = Z_N(\Omega; 1). \]

As the identity matrix 1 obviously satisfies the condition (66), $Z_N(\Omega)$ is of dimension $K$ and a basis is given by (73). Next, we introduce the (closed) subspace of $H(\text{div}; \Omega)$:

\[ H^\Gamma(\text{div}; \Omega) := \{ v \in H(\text{div}; \Omega) : (v \cdot n, 1)_{H^\frac{1}{2}(\Gamma)} = 0, \ 1 \leq k \leq K \}. \]

As an immediate consequence of Proposition 5.3, we have...
**Proposition 5.5.** Let $\Omega$ a domain. The following orthogonal decomposition of the space $H(\text{div} \, 0; \Omega)$ holds:

$$H(\text{div} \, 0; \Omega) = Z_N(\Omega) \oplus H^\Gamma(\text{div} \, 0; \Omega).$$

Now, we can prove the following compactness result.

**Theorem 5.6.** Let $\Omega$ be a domain. The embedding of the space $X_{N, \Gamma}(\Omega; \mathbb{B})$ into $L^2(\Omega)$ is compact.

**Proof.** Let $(v_n)_{n \in \mathbb{N}}$ be a bounded sequence of $X_{N, \Gamma}(\Omega; \mathbb{B})$. According to Lemma 5.2, there exists two sequences $(q_n)_{n \in \mathbb{N}}$ and $(u_n)_{n \in \mathbb{N}}$ of elements, respectively, of $H^1_0(\Omega)$ and $L^2(\Omega)$, such that $v_n = \text{grad} \, q_n + u_n^T$ for all $n$. Our aim, using this decomposition, is to prove that a subsequence of $(v_n)$ converges strongly in $L^2(\Omega)$. This is done in two steps.

**Step 1.** According to (72), the sequence $(q_n)$ satisfies, for all $n$: $\|\text{grad} \, q_n\| \leq C\|v_n\|$, with $C$ independent of $v_n$. So, $(q_n)$ is bounded in $H^1_0(\Omega)$, and since $H^1_0(\Omega)$ is compactly embedded into $L^2(\Omega)$, there exists a subsequence, still denoted by $(q_n)$, that converges strongly in $L^2(\Omega)$. Now, let us show that the subsequence $(\text{grad} \, q_n)$ converges in $L^2(\Omega)$. Denote $v_{nm} := v_n - v_m$ and $q_{nm} := q_n - q_m$. By construction, the sequence $(q_{nm})$ verifies $\text{div} \, \mathbb{B}v_n = \text{div} \, \mathbb{B} \text{grad} \, q_n$, for all $n \in \mathbb{N}$. This leads to the inequality

$$|\langle \text{div} \, \mathbb{B} \text{grad} \, q_{nm} \rangle | = |\langle \text{div} \, \mathbb{B}v_{nm} \rangle | \leq 2\sup_n \|v_n\| X_{N, \Gamma}(\Omega) \|q_{nm}\| \leq C' \|q_{nm}\|.$$  

On the other hand, from (66) and the integration-by-parts formula (67), we deduce:

$$|\langle \text{div} \, \mathbb{B} \text{grad} \, q_{nm} \rangle | = |\langle \mathbb{B} \text{grad} \, q_{nm} | \text{grad} \, q_{nm} \rangle | \geq \zeta \|\text{grad} \, q_{nm}\|.$$  

Combining the above, we conclude:

$$\|\text{grad} \, q_n - \text{grad} \, q_m\| \leq \frac{C'}{\zeta} \|q_{nm}\|.$$  

So, $(\text{grad} \, q_n)$ is a Cauchy sequence in $L^2(\Omega)$, and therefore it converges in this space.

**Step 2.** Recall that the sequence $(u_n^T)_{n}$ verifies $\text{div} \, u_n^T = 0$, $\text{curl} \, u_n^T = \text{curl} \, v_n$ and $v_n \times n|_\Gamma = v_n \times n|_\Gamma$. By Proposition 5.5, there exists a sequence $(y_n)_{n}$ of elements of $H^1(\text{div} \, 0; \Omega)$ and a sequence $(z_n)_{n}$ on $Z_N(\Omega)$ such that $\mathbb{B}u_n^T = z_n + y_n$ for all $n$. The sequence $(z_n)$ is bounded in the finite-dimensional space $Z_N(\Omega)$, so there exists a subsequence, still denoted by $(z_n)$, which converges in any norm, e.g., that of $L^2(\Omega)$. Then, according to [3, Theorem 3.4.1], there exists a sequence $(w_n)$ of elements of $H^1(\Omega)$ such that $y_n = \text{curl} \, w_n$ for all $n$, and it satisfies:

$$\|w_n\|_{H^1(\Omega)} \leq \xi \|y_n\|$$  

for some $\xi > 0$. As $(y_n)$ is bounded in $L^2(\Omega)$, it follows that $(w_n)$ is bounded in $H^1(\Omega)$. As the trace mapping is continuous from $H^1(\Omega)$ to $H^\frac{1}{2}(\Gamma)$, it follows that $(w_n|_\Gamma)$ is bounded in $H^\frac{1}{2}(\Gamma)$. Therefore, by Sobolev’s compact embedding theorem, we can extract a subsequence, still denoted by $(w_n)$, that converges in $L^2(\Gamma)$ and such that $(w_n|_\Gamma)$ converges in $L^2(\Gamma)$. Denote $v_{nm}^T := v_n^T - v_m^T$, $w_{nm} := w_n - w_m$, and $z_{nm} := z_n - z_m$. According to the condition (66), $\mathbb{B}$ is invertible, and we find

$$|\langle \mathbb{B}^{-1}(z_{nm} + \text{curl} \, w_{nm}) | z_{nm} + \text{curl} \, w_{nm} \rangle | = |\langle v_{nm}^T | Bv_{nm}^T \rangle | \geq \zeta \|v_{nm}^T\|.$$  

Next, by integration by parts (18), we obtain
\[
\left| \left( B z_{nm} + \text{curl} w_{nm} \right) \right| = \left| \left( v_{nm}^T z_{nm} + \text{curl} w_{nm} \right) \right| = \left\| \left( v_{nm}^T z_{nm} + \text{curl} w_{nm} \right) \right\|_{L^2(\Gamma)} \leq 2 \sup_n \left\| v_{nm} \right\|_{X_N,\Gamma(\Omega;B)} \left( \left\| z_{nm} \right\| + \left\| w_{nm} \right\| + \left\| w_{nm} \right\|_{L^2(\Gamma)} \right).
\]
Combining the above, we find
\[
\left\| v_{n}^T - v_{m}^T \right\|_{L^2(\Omega)} \leq C' \left( \left\| z_{nm} \right\| + \left\| w_{nm} \right\| + \left\| w_{nm} \right\|_{L^2(\Gamma)} \right). 
\]
So, \((v_{n}^T)\) is a Cauchy sequence in \(L^2(\Omega)\), and it converges in this space. Finally, the subsequence \((v_n)\), defined by \(v_n := \text{grad} q_n + v_n^T\), converges in \(L^2(\Omega)\).

5.3.2. Equivalent norms on \(X_{N,\Gamma}(\Omega;B)\)

As a consequence of Theorem 5.6, there holds a basic inequality. The proof follows the lines of [3, Thm 3.4.3] and [12, Proposition 7.4].

**Proposition 5.7.** There exists a constant \(C > 0\) such that
\[
\forall v \in X_{N,\Gamma}(\Omega;B), \quad \left\| v \right\| \leq C \left\{ \left\| \text{curl} v \right\| + \left\| \text{div} B v \right\| + \left\| v \right\|_{L^2(\Gamma)} + |P_{Z_N(\Omega;B)}v|_{Z_N(\Omega;B)} \right\}. \tag{75}
\]

**Corollary 5.8.** The semi-norm
\[
|v|_{X_{N,\Gamma}(\Omega;B)} = \left( \left\| \text{curl} v \right\|^2 + \left\| \text{div} B v \right\|^2 + \left\| v \right\|_{L^2(\Gamma)}^2 + |P_{Z_N(\Omega;B)}v|_{Z_N(\Omega;B)} \right)^{\frac{1}{2}}.
\]
is a norm in \(X_{N,\Gamma}(\Omega;B)\), equivalent to the natural norm.

6. Spectral properties of some useful matrices

We still denote \(\| \cdot \|_M\) the operator norm of \(M_3(\mathbb{C})\) induced by the Hermitian norm of \(\mathbb{C}^3\). In the rest of the paper, in addition to Hypothesis 1, we shall make the following...
Proof. First, we determine the matrix $M_s$. At each point $x \in \Omega$, we consider an orthonormal Stix frame \[ (e_1(x), e_2(x), e_3(x) = b(x)). \] In this frame, the expression of $M_s$ writes:

$$M_s = \begin{pmatrix}
 \nu_s & -\Omega cs & 0 \\
 \Omega cs & \nu_s & 0 \\
 0 & 0 & \nu_s
\end{pmatrix}.$$  

Hence we deduce the expression

$$\text{i} \alpha I + M_s = \begin{pmatrix}
 \text{i} \alpha + \nu_s & -\Omega cs & 0 \\
 \Omega cs & \text{i} \alpha + \nu_s & 0 \\
 0 & 0 & \text{i} \alpha + \nu_s
\end{pmatrix}.$$ 

The determinant of this matrix is:

$$\det(\text{i} \alpha I + M_s) = (\text{i} \alpha + \nu_s) \left[ (\text{i} \alpha + \nu_s)^2 + \Omega_{cs}^2 \right] = (\text{i} \alpha + \nu_s) \left[ (\Omega_{cs}^2 + \nu_s^2 - \alpha^2) + 2i \alpha \nu_s \right] =: d_s.$$ 

By Hypothesis 2, for $\alpha \in \mathbb{R}$ fixed it holds that $|d_s(x)| \geq d_\alpha > 0$ a.e. on $\Omega$. Thus, the matrix $\text{i} \alpha I + M_s$ is invertible, and the usual inversion formula gives:

$$(\text{i} \alpha I + M_s)^{-1} = \frac{1}{d_s} \begin{pmatrix}
 (\text{i} \alpha + \nu_s)^2 & \Omega_{cs}(\text{i} \alpha + \nu_s) & 0 \\
 -\Omega_{cs}(\text{i} \alpha + \nu_s) & (\text{i} \alpha + \nu_s)^2 & 0 \\
 0 & 0 & (\text{i} \alpha + \nu_s)^2 + \Omega_{cs}^2
\end{pmatrix}.$$ 

We can check that the above matrix is normal (i.e., it commutes with its conjugate transpose). By [10, Theorem 1.4-2], we deduce that the $\| \cdot \|_M$ norm of $(\text{i} \alpha I + M_s)^{-1}$ is equal to its spectral radius. Therefore, to prove that $(\text{i} \alpha I + M_s)^{-1}$ is uniformly bounded it suffices to bound its spectral radius on $\Omega$. Its eigenvalues are:

$$\frac{(\text{i} \alpha + \nu_s)^2 \pm i \Omega_{cs}(\text{i} \alpha + \nu_s)}{d_s} \quad \text{and} \quad \frac{(\text{i} \alpha + \nu_s)^2 + \Omega_{cs}^2}{d_s}.$$ 

According to Hypothesis 1 and the above, these eigenvalues are bounded on $\Omega$. □

From Hypotheses 1 and 2 there follows:

**Proposition 6.2.** Let $\alpha \in \mathbb{R}$. Let $D_\alpha : \Omega \to M_3(\mathbb{C})$ be the matrix

$$D_\alpha(x) := \sum_s \omega_{ps}^2(x)(\text{i} \alpha I + M_s(x))^{-1}, \quad \text{for} \ x \in \Omega.$$ (77)

Then, $D_\alpha$ is uniformly bounded on $\Omega$.

Let $\alpha \in \mathbb{R}$. We now introduce another matrix which will play an important role in the proofs of stability.

$$B_\alpha := \text{i} \alpha I + D_\alpha := \begin{pmatrix}
 P & Q & 0 \\
 -Q & P & 0 \\
 0 & 0 & R
\end{pmatrix}.$$ (78)
where the functions $P$, $Q$ and $R$ are given by

\[
P(x) := i\alpha + \sum_s \frac{\omega_{ps}^2(x)(i\alpha + \nu_s(x))}{(i\alpha + \nu_s(x))^2 + \Omega_{cs}^2(x)},
\]

\[
Q(x) := \sum_s \frac{\omega_{ps}^2(x)\Omega_{cs}(x)}{(i\alpha + \nu_s(x))^2 + \Omega_{cs}^2(x)},
\]

\[
R(x) := i\alpha + \sum_s \frac{\omega_{ps}^2(x)}{i\alpha + \nu_s(x)}.
\]

The matrix $B_\alpha$ is normal ($B_\alpha B_\alpha^* = B_\alpha^* B_\alpha$), and its eigenvalues are

\[\lambda_{\alpha,1} = P + iQ, \quad \lambda_{\alpha,2} = P - iQ, \quad \lambda_{\alpha,3} = R.\]

According to Proposition 6.2, we deduce that $B_\alpha$ is uniformly bounded on $\Omega$, i.e., there exists a constant $\eta_\alpha > 0$ depending on $\alpha$ such that

\[\sup_{x \in \Omega} \|B_\alpha(x)\|_M \leq \eta_\alpha.\]

**Proposition 6.3.** Let $\alpha \in \mathbb{R}$. Then, the real parts of $(\lambda_{\alpha,j})_{j=1,2,3}$ are uniformly bounded below on $\Omega$. We then define $\zeta_\alpha$ to be

\[\zeta_\alpha := \min_{j=1,2,3} \inf_{x \in \Omega} \Re(\lambda_{\alpha,j}(x)) > 0.\]

**Proof.** From (79)–(81), one obtains the expression of the real parts of the eigenvalues of $B_\alpha$:

\[
\Re(\lambda_{\alpha,1}(x)) = \sum_s \frac{\omega_{ps}^2(x)\nu_s(x)}{(\Omega_{cs}^2(x) + \nu_s^2(x) - \alpha^2)^2 + 4\alpha^2\nu_s^2(x)} \left[ (\Omega_{cs}(x) + \alpha)^2 + \nu_s^2(x) \right],
\]

\[
\Re(\lambda_{\alpha,2}(x)) = \sum_s \frac{\omega_{ps}^2(x)\nu_s(x)}{(\Omega_{cs}^2(x) + \nu_s^2(x) - \alpha^2)^2 + 4\alpha^2\nu_s^2(x)} \left[ (\Omega_{cs}(x) - \alpha)^2 + \nu_s^2(x) \right],
\]

\[
\Re(\lambda_{\alpha,3}(x)) = \sum_s \frac{\omega_{ps}^2(x)\nu_s(x)}{\nu_s^2(x) + \alpha^2}.
\]

Due to Hypothesis 2 and assumption (23), one deduces that these real parts are strictly positive. The rest of the proof follows by Hypotheses 1 and 2.

**Lemma 6.4.** Given $\alpha \in \mathbb{R}$, it holds that

\[\eta_\alpha(v^*v) \geq |v^*B_\alpha(x)v| \geq \Re[v^*B_\alpha(x)v] \geq \zeta_\alpha(v^*v), \quad \forall v \in \mathbb{C}^3, \quad \forall x \in \Omega.\]

**Remark 6.5.** According to Lemma 6.4, we can apply all the results of Subsection 5.2 to the matrix $B_\alpha$, for $\alpha \in \mathbb{R}$.

7. **Strong stability**

We define the energy of our model as $E(t) := \frac{1}{2}\|U\|_{X_t}^2$. With the definition (6) of the plasma pulsation, the term given by the $J_s$ variables is interpreted as the kinetic energy of the particles: $\frac{|J_s|^2}{\omega_{ps}} \propto n_s |U_s|^2$ at dominant
order; while the \((E, B)\) part is the electromagnetic energy of the wave. If \(U_0\) satisfies the condition (63), then, using the Green formula (18), one easily finds that:

\[
\frac{d}{dt} E(t) = -\frac{1}{\varepsilon_0} \sum_s \left\| \frac{\sqrt{\varepsilon_0}}{\omega_{ps}} J_s \right\|^2 - \varepsilon_0 c^2 \int_{\Gamma_A} (c|B| \cdot g - B \cdot \nabla) d\Gamma.
\]

Here, \(\Gamma_A\) is arbitrary. The above equation shows that the energy is non-increasing if \(\Gamma_A = \emptyset\) or \(g = 0\). (On the other hand, if \(\Gamma_A = \emptyset\) and \(\nu_s = 0\), the derivative vanishes and \(E(t) = E(0)\) for all \(t > 0\); this justifies Hypothesis 2.)

Therefore, we will study the decay of the energy in both cases: perfectly conducting (\(\Gamma_A = \emptyset\)) and homogeneous Silver–Müller (\(\Gamma_A \neq \emptyset\) and \(g = 0\)). Notice that, as a consequence of Hypotheses 1 and 2, the spaces \(L^2_s(\Omega)\) are equal to \(L^2(\Omega)\), and the norms \(\|\cdot\|_s\) and \(\|\cdot\|_x\) are equivalent. Similarly, the norm \(\|\cdot\|_X\) is equivalent to the canonical norm of \(L^2(\Omega)^4\).

For \(\ell = 1, 2\), the domain \(D(A_\ell)\) is not compactly embedded into \(X\); thus, the resolvent of \(A_\ell\) is not compact, as said in the Introduction. This fact precludes the use of many operator-theoretical results. To show the strong stability we shall use the general criterion of Arendt–Batty and Lyubich–Vu [2,17].

**Theorem 7.1** (Arendt–Batty / Lyubich–Vu). Let \(X\) be a reflexive Banach space and \((T(t))_{t \geq 0}\) be a \(C_0\)-semigroup on \(X\) generated by \(L\). Assume that \((T(t))_{t \geq 0}\) is bounded and no eigenvalue of \(L\) lies on the imaginary axis. If \(\sigma(L) \cap i\mathbb{R}\) is countable, then \((T(t))_{t \geq 0}\) is strongly stable.

**7.1. Perfectly conducting case**

**Proposition 7.2.** For all \(\alpha \in \mathbb{R} \setminus \{0\}\), the operator \(i\alpha I + A_1\) is injective, i.e.,

\[
\ker(i\alpha I + A_1) = \{0\}.
\]

Furthermore, 0 is an eigenvalue of \(A_1\) and the corresponding set of eigenvectors is:

\[
\ker A_1 = \{(0, 0, 0, V) : V \in H(\text{curl} 0; \Omega)\}.
\]

**Proof.** Let \(\alpha \in \mathbb{R}\) and \(U = (U_1, U_2, U_3, U_4)^T \in D(A_1)\) such that

\[
(i\alpha I + A_1) U = 0.
\]

This is equivalent to the system

\[
i\alpha U_1 + M_1 U_1 - \varepsilon_0 \omega^2_{p_1} U_3 = 0,
\]

\[
i\alpha U_2 + M_2 U_2 - \varepsilon_0 \omega^2_{p_2} U_3 = 0,
\]

\[
i\alpha U_3 + \frac{1}{\varepsilon_0} U_1 + \frac{1}{\varepsilon_0} U_2 - c^2 \text{curl} U_4 = 0,
\]

\[
i\alpha U_4 + \text{curl} U_3 = 0.
\]

Taking the real part of the inner product of (85) with \(U\) in \(X\), one gets:

\[
\Re(i\alpha \|U\|_X^2) = \Re(\langle A_1 U, U \rangle_X) = 0.
\]
By the monotonicity of $A_1$, see Equation (35), one obtains:

$$
\begin{pmatrix}
\nu_s U_s \\
\varepsilon_0 \omega_{ps}
\end{pmatrix}
\begin{pmatrix}
U_s \\
\omega_{ps}
\end{pmatrix}
= 0, \quad s = 1, 2. \tag{90}
$$

By Hypothesis 2:

$$
\begin{pmatrix}
\nu_s U_s \\
\varepsilon_0 \omega_{ps}
\end{pmatrix}
\begin{pmatrix}
U_s \\
\omega_{ps}
\end{pmatrix}
\geq \frac{\nu_s}{\varepsilon_0} \| U_s \|^2_{(s)}, \quad s = 1, 2. \tag{91}
$$

From Equations (90) and (91), we deduce that

$$
U_1 = 0 \quad \text{and} \quad U_2 = 0 \quad \text{in} \ \Omega. \tag{92}
$$

This, together with Equation (86), implies that

$$
U_3 = 0 \quad \text{in} \ \Omega. \tag{93}
$$

If $\alpha \neq 0$, $U_4 = 0$ follows from (93) and (89). And if $\alpha = 0$, we deduce from (88), (92) and (93) that $\text{curl}U_4 = 0$. The proof of the proposition is complete. \hfill \Box

Therefore, $\ker A_1$ consists of the space of stationary solutions to Problem (10)–(14) with boundary condition (15), and it is of infinite dimension. From Remark 4.11, we can define the operator $A_1 | X_1 : D(A_1) \cap X_1 \to X_1$ the restriction of $A_1$ on the space $X_1$. In this case, the set of stationary solutions of the problem formed by Equations (10)–(14) and (9), with the boundary conditions (15) and (17), is equal to

$$
\ker(A_1 | X_1) = \{0\}^3 \times Z_T(\Omega),
$$

where the kernel

$$
Z_T(\Omega) := H(\text{curl} 0; \Omega) \cap H_0(\text{div} 0; \Omega).
$$

We recall that the space $Z_T(\Omega)$ is of dimension $J$, the number of cuts [1, 3] (if $\Omega$ is topologically trivial then $Z_T(\Omega) = \{0\}$). Consider $(\text{grad} \hat{q}_j)_{1 \leq j \leq J}$ a basis of $Z_T(\Omega)$ given by [1, Proposition 3.14] where $\hat{q}_j \in H^1(\Omega)$ is a function such that (among other conditions) $(\text{grad} \hat{q}_j \cdot n)_{\Sigma_i} = \delta_{ji}$ for $i = 1, \ldots, J$. From this basis we deduce the following orthogonal decomposition in $H_0(\text{div} 0; \Omega)$:

$$
H_0(\text{div} 0; \Omega) = Z_T(\Omega) \bigoplus H_0^\Sigma(\text{div} 0; \Omega), \tag{94}
$$

where

$$
H_0^\Sigma(\text{div} 0; \Omega) := \{v \in H_0(\text{div} 0; \Omega) : (v \cdot n)_{\Sigma_j} = 0, \ 1 \leq j \leq J\}.
$$

Then, according to (94) and by [3, Propositions 3.7.3 and 3.7.4], we have the following decomposition

$$
L^2(\Omega) = H(\text{curl} 0; \Omega) \bigoplus H_0^\Sigma(\text{div} 0; \Omega). \tag{95}
$$

**Proposition 7.3.** For all $\alpha \in \mathbb{R} \setminus \{0\}$, the operator $i\alpha I + A_1$ is surjective, i.e.,

$$
\text{im} \ (i\alpha I + A_1) = X.
$$
Proof. We take any \( \alpha \in \mathbb{R} \setminus \{0\} \) and any \( F = (F_1, F_2, F_3, F_4)^\top \in X \), and we look for \( U = (U_1, U_2, U_3, U_4)^\top \in D(A_1) \), which solves

\[
(\alpha I + A_1)U = F. 
\]

Equivalently, according to (27), we consider the following system

\[
\begin{align*}
\alpha U_1 + M_1 U_1 - \varepsilon_0 \omega_{p_1}^2 U_3 &= F_1, \\
\alpha U_2 + M_2 U_2 - \varepsilon_0 \omega_{p_2}^2 U_3 &= F_2, \\
\alpha U_3 + \frac{1}{\varepsilon_0} U_1 + \frac{1}{\varepsilon_0} U_2 - c^2 \text{curl} U_4 &= F_3, \\
\alpha U_4 + \text{curl} U_3 &= F_4.
\end{align*}
\]

Using (97), (98) and (100), we keep \( U_3 \) as the main unknown and eliminate the others:

\[
\begin{align*}
U_1 &= (\alpha I + M_1)^{-1}(F_1 + \varepsilon_0 \omega_{p_1}^2 U_3), \\
U_2 &= (\alpha I + M_2)^{-1}(F_2 + \varepsilon_0 \omega_{p_2}^2 U_3), \\
U_4 &= (\alpha)^{-1}(F_4 - \text{curl} U_3).
\end{align*}
\]

Inserting these expressions into (99), we obtain an equation in \( U_3 \):

\[
\alpha U_3 + \frac{c^2}{\alpha} \text{curl} \text{curl} U_3 + D_\alpha U_3 = F_3 + \frac{c^2}{\alpha} \text{curl} F_4 - \frac{1}{\varepsilon_0} \sum_s (\alpha I + M_s)^{-1} F_s. 
\]

Here, we cannot apply the Lax–Milgram theorem as in Proposition 4.5: the operator on the left-hand side (even suitably rescaled) is not positive. So, we shall solve this problem with a suitable version of the Fredholm alternative for constrained problems, as in [3, §4.5.1]. Taking account of the constraints is necessary in order to give some compactness properties (by Theorem 5.6), which are not furnished by the definition of our evolution operator.

Thus, we introduce the following mixed formulation for (104):

Find \( (U_3, p) \in H_0(\text{curl}; \Omega) \times H_0^1(\Omega) \) such that

\[
\begin{align*}
a_\alpha(U_3, v) + c_\alpha(U_3, v) + b_\alpha(v, p) &= L_\alpha(v), \quad \forall v \in H_0(\text{curl}; \Omega), \\
b_\alpha(U_3, q) &= (G | \text{grad} q),
\end{align*}
\]

where the sesquilinear forms \( a_\alpha, c_\alpha \) and \( b_\alpha \) are respectively defined on \( H_0(\text{curl}; \Omega) \times H_0(\text{curl}; \Omega), L^2(\Omega) \times H_0(\text{curl}; \Omega) \) and \( H_0(\text{curl}; \Omega) \times H_0^1(\Omega) \) as:

\[
\begin{align*}
a_\alpha(w, v) &:= (\alpha)^{-1} c^2 (\text{curl} w | \text{curl} v), \\
c_\alpha(w, v) &:= (\mathbb{B}_\alpha w | v), \quad \text{where} \quad \mathbb{B}_\alpha = \alpha I + D_\alpha, \\
b_\alpha(v, q) &:= (\mathbb{B}_\alpha v | \text{grad} q).
\end{align*}
\]

The anti-linear form \( L_\alpha \) on \( H_0(\text{curl}; \Omega) \) is given by:

\[
L_\alpha(v) := (F_3 | v) + \frac{c^2}{\alpha} (F_4 | \text{curl} v) - \frac{1}{\varepsilon_0} \sum_s ((\alpha I + M_s)^{-1} F_s | v),
\]

and \( G \) is an element of \( L^2(\Omega) \) which will be chosen later.
To show the well-posedness of the variational formulation (105)–(106), we first verify that the assumptions of [3, Theorem 4.5.9] on Helmholtz-like problems with constraints are fulfilled, and we conclude by the Fredholm alternative.

**i) Continuity:** it is clear that the sesquilinear forms $a_\alpha$, $b_\alpha$ and $c_\alpha$, and the anti-linear from $L_\alpha$, are continuous on their respective spaces.

**ii) Coercivity on the kernel:** the kernel of $b_\alpha$ is defined by

$$K = \{ v \in H_0(\text{curl}; \Omega) : b_\alpha(v, q) = 0, \quad \forall q \in H^1_0(\Omega) \}$$

which, by Green’s formulas (68) and (67), can be written as

$$K = \{ v \in H_0(\text{curl}; \Omega) \cap H(\text{div}, \mathbb{B}_\alpha; \Omega) : (\mathbb{B}_\alpha v \cdot n, 1)_{H^1(\Gamma_k)} = 0, \quad \forall 1 \leq k \leq K \} = \{ v \in H_0(\text{curl}; \Omega) \cap H(\text{div}, \mathbb{B}_\alpha; \Omega) : P_{Z_\alpha}(\Omega, \mathbb{B}_\alpha) v = 0 \}.$$ 

According to Corollary 5.8 applied to the closed subspace $K$ of $X_{N,1}(\Omega; \mathbb{B})$, the sesquilinear form $a_\alpha$ is coercive on $K \times K$. Furthermore, the embedding $K \subset L^2(\Omega)$ is compact by Theorem 5.6.

**iii) Inf-sup condition:** let $q \in H^1_0(\Omega)$ and set $v = \text{grad} q \in H_0(\text{curl}; \Omega)$, thus $v$ checks $\| v \|_{H(\text{curl}; \Omega)} = (\| v \|^2 + \| \text{curl} v \|^2)^{1/2} = \| v \|$. On the other hand, according to Lemma 6.4, one has

$$| b_\alpha(v, q) | = | (\mathbb{B}_\alpha v \mid \text{grad} q) | = | (\mathbb{B}_\alpha v \mid v) | \geq \zeta_\alpha \| v \|^2 = \zeta_\alpha \| v \| \| \text{grad} q \|. \quad (111)$$

Combining the above, it follows that

$$\frac{| b_\alpha(v, q) |}{\| v \|_{H(\text{curl}; \Omega)}} \geq \zeta_\alpha \| \text{grad} q \| = \zeta_\alpha \| q \|_{H^1_0(\Omega)}. \quad (112)$$

Consequently, there exists $C_b = \zeta_\alpha > 0$ such that

$$\forall q \in H^1_0(\Omega), \quad \sup_{v \in H_0(\text{curl}; \Omega)} \frac{| b_\alpha(v, q) |}{\| v \|_{H(\text{curl}; \Omega)}} \geq C_b \| q \|_{H^1_0(\Omega)}.$$ 

Hence, the assumptions of [3, Theorem 4.5.9] are satisfied: we can apply the usual Fredholm alternative [3, Theorem 4.5.7]. So, we show that the variational formulation (105) is injective on the kernel, i.e., its solution is unique. Let $Z_3$ be a solution to

$$\forall v \in K, \quad a_\alpha(Z_3, v) + c_\alpha(Z_3, v) = 0. \quad (113)$$

Since $Z_3$ belongs to $K$, one has $Z_3 \in H(\text{curl}; \Omega)$ with $\text{div} \mathbb{B}_\alpha Z_3 = 0$ in $\Omega$ and $Z_3 \times n_{|\Gamma} = 0$. Next, consider $y \in D(\Omega)$. Introduce the scalar field $\varphi \in H^1_0(\Omega)$ that solves the variational formulation: for all $\psi \in H^1_0(\Omega)$, $(\mathbb{B}_\alpha \text{grad} \varphi \mid \text{grad} \psi) = (\mathbb{B}_\alpha y \mid \text{grad} \psi)$. By construction, $v := y - \text{grad} \varphi$ belongs to $K$ with $\text{curl} v = \text{curl} y$. Using it as a test function in (113) yields

$$\langle (\alpha)^{-1} c^2 \text{curl} \text{curl} Z_3 + \mathbb{B}_\alpha Z_3, y \rangle = (\alpha)^{-1} c^2 (\text{curl} Z_3 \mid \text{curl} y) + (\mathbb{B}_\alpha Z_3 \mid y) = (\alpha)^{-1} c^2 (\text{curl} Z_3 \mid \text{curl} v) + (\mathbb{B}_\alpha Z_3 \mid v + \text{grad} \varphi) = (\alpha)^{-1} c^2 (\text{curl} Z_3 \mid \text{curl} v) + (\mathbb{B}_\alpha Z_3 \mid v) = 0.$$
The last line is obtained by integration by parts, using the facts that \( \text{div}(\mathbb{B}_\alpha Z_3) = 0 \) in \( \Omega \) and \( (\mathbb{B}_\alpha Z_3 \cdot n, 1)_{\mathbf{H}^1_0(\gamma_a)} = 0 \), for all \( 1 \leq k \leq K \). Recall that \( \mathbb{B}_\alpha = \text{ia}1 + \mathbb{D}_\alpha \); as \( y \) is arbitrary, it follows that:

\[
\text{ia}Z_3 + (\text{ia})^{-1}c^2 \text{curl} Z_3 + \mathbb{D}_\alpha Z_3 = 0, \quad \text{in } \mathcal{D}'(\Omega).
\]

(114)

Let now \( Z_1, Z_2 \) and \( Z_4 \) defined as

\[
(\text{ia}I + M_s)Z_s = \varepsilon_0 \omega^2_{ps} Z_3, \quad s = 1, 2; \quad Z_4 = -(\text{ia})^{-1} \text{curl} Z_3.
\]

(115)

Clearly, these fields belong to \( \mathbf{L}^2(\Omega) \). Replacing the matrix \( \mathbb{D}_\alpha \) with its expression in (114) and using the definitions above, we get

\[
\text{ia}Z_3 + \frac{1}{\varepsilon_0} Z_1 + \frac{1}{\varepsilon_0} Z_2 - c^2 \text{curl} Z_4 = 0,
\]

which implies that \( \text{curl} Z_4 \in \mathbf{L}^2(\Omega) \). The equations (115)–(116) are equivalent to \( (\text{ia}I + A_1)Z = 0 \), with \( Z = (Z_1, Z_2, Z_3, Z_4)^\top \in D(A_1) \). Therefore, according to Proposition 7.2, one finds \( Z = 0 \), and so \( Z_3 = 0 \) in \( \Omega \). Thus, the formulation (113) is injective. Finally, according to Theorem 4.5.9 and Proposition 4.5.8 of [3], the problem (105)–(106) has a unique solution \( (U_3, p) \in \mathbf{H}_0(\text{curl}; \Omega) \times \mathbf{H}^1_{\text{div}}(\Omega) \).

To show the equivalence between (105) and the strong formulation (104), we have to check that the Lagrange multiplier \( p \) vanishes. Taking \( v = \text{grad} p \in \mathbf{H}_0(\text{curl}; \Omega) \) as a test function in (105), we obtain

\[
(\mathbb{B}_\alpha U_3 | \text{grad} p) + (\mathbb{B}_\alpha \text{grad} p | \text{grad} p) = (F_3 | \text{grad} p) - \frac{1}{\varepsilon_0} \sum_s ((\text{ia}I + M_s)^{-1} F_s | \text{grad} p).
\]

(117)

The first term above is the left-hand side of the constraint equation (106). Thus, choosing

\[
G := F_3 - \frac{1}{\varepsilon_0} \sum_s ((\text{ia}I + M_s)^{-1} F_s) \in \mathbf{L}^2(\Omega),
\]

(118)

we get, according to (117) and (106),

\[
(\mathbb{B}_\alpha \text{grad} p | \text{grad} p) = 0.
\]

Thanks to Lemma 6.4, we deduce that \( \text{grad} p = 0 \) in \( \Omega \). As \( p \) belongs to \( \mathbf{H}^1_{\text{div}}(\Omega) \), we find \( p = 0 \).

Returning to Problem (96), we define \( U_1 \in \mathbf{L}^2(\Omega) \), \( U_2 \in \mathbf{L}^2(\Omega) \) respectively by (101) and (102). Also, we define \( U_4 \in \mathbf{L}^2(\Omega) \) by (103). Taking \( v \in \mathcal{D}(\Omega) \) as a test function in (105), replacing \( \mathbb{B}_\alpha \) with its expression and using Green’s formula (18), we obtain Equation (104), and by the definition (103) of \( U_4 \) we find

\[
\text{ia}U_3 - c^2 \text{curl} U_4 + \mathbb{D}_\alpha U_3 = F_3 - \frac{1}{\varepsilon_0} \sum_s ((\text{ia}I + M_s)^{-1} F_s) \quad \text{in } \mathcal{D}'(\Omega).
\]

(119)

This implies that \( \text{curl} U_4 \in \mathbf{L}^2(\Omega) \). To finish the proof, it remains to check that Equation (99) is satisfied: to this end, it is enough to replace in (119) the matrix \( \mathbb{D}_\alpha \) with its definition and to use (101) and (102).

Let us introduce a closed subspace of \( \mathbf{X} \):

\[
\tilde{\mathbf{X}}_1 := \mathbf{L}^2(\Omega) \times \mathbf{L}^2(\Omega) \times \mathbf{L}^2(\Omega) \times \mathbf{H}^1_0(\text{div}; \Omega).
\]

(120)

Of course, \( \tilde{\mathbf{X}}_1 \) is a Hilbert space when endowed with the inherited inner product.

**Proposition 7.4.** The range \( \text{im}(A_1) \) of \( A_1 \) is included in \( \tilde{\mathbf{X}}_1 \).
Proof. Consider \( U = (U_1, U_2, U_3, U_4)^\top \) an element of \( D(\tilde{A}_1) \). Then, by the definition (31) of \( A_1, \tilde{A}_1U \) belongs to \( \tilde{X}_1 \) if, and only if, \( \text{curl}U_3 \) belongs to \( H_0^0(\text{div}; \Omega) \). But \( U_3 \in H_0^0(\text{curl}; \Omega) \), and it is well-known (see, \( v.g., [3, \text{Remark 3.5.2}] \)) that \( v \in H_0^0(\text{curl}; \Omega) \) implies \( \text{curl}v \in H_0^0(\text{div}; \Omega) \). 

The spectral analysis of the operator \( A_1 \) shows that no stabilization can take place in the whole space \( X \): an initial data \( U_0 \in \ker A_1 \) generates a constant-in-time solution. The above results lead us to introduce the unbounded operator \( \tilde{A}_1 : D(\tilde{A}_1) \to \tilde{X}_1 \) defined by

\[
D(\tilde{A}_1) = D(A_1) \cap \tilde{X}_1 \quad \text{and} \quad \tilde{A}_1U = A_1U, \quad \forall U \in D(\tilde{A}_1). \tag{121}
\]

The spectral properties of \( \tilde{A}_1 \) are easily deduced from Propositions 7.2 and 7.3.

**Proposition 7.5.** For all \( \alpha \in \mathbb{R} \), the operator \( i\alpha I + \tilde{A}_1 \) is injective. For \( \alpha \in \mathbb{R} \setminus \{0\} \), it is surjective.

*Proof.** The injectivity for \( \alpha \neq 0 \) directly follows from Proposition 7.2. For \( \alpha = 0 \), \( \tilde{A}_1U = 0 \) means \( U \in \tilde{X}_1 \) and \( \tilde{A}_1U = 0 \), hence \( U_1 = U_2 = U_3 = 0, U_4 \in H(\text{curl}0; \Omega) \) and \( U_4 \in H_0^0(\text{div}0; \Omega) \). According to (95), this implies \( U_4 = 0 \).

Taking account of Proposition 7.3, the surjectivity property means that, if \( F \in \tilde{X}_1 \), the unique solution \( U \) to \( i\alpha U + \tilde{A}_1U = F \) belongs to \( \tilde{X}_1 \). This, in turn, is an obvious consequence of Proposition 7.4. \( \square \)

We notice that \( \tilde{X}_1 \) is an invariant space for the problem (32), see Lemma 7.8. We then define \( \tilde{T}_1 := T_{1|D(\tilde{A}_1)\cap \tilde{X}_1} \).

**Theorem 7.6.** The semigroup of contractions \( (\tilde{T}_1(t))_{t \geq 0} \) with generator \( -\tilde{A}_1 \) is strongly stable on the energy space \( \tilde{X}_1 \), i.e.,

\[
\lim_{t \to +\infty} \|\tilde{T}_1(t)\tilde{U}_0\|_{\tilde{X}_1} = 0, \quad \forall \tilde{U}_0 \in \tilde{X}_1. \tag{122}
\]

*Proof.** According to Proposition 7.5, we conclude that

\[
\sigma(-\tilde{A}_1) \cap i\mathbb{R} = \emptyset \quad \text{or} \quad \{0\},
\]

which is countable in both cases, and that 0 is not an eigenvalue. On the other hand, \( \tilde{A}_1 \) is monotone in \( \tilde{X}_1 \), so \( -\tilde{A}_1 \) is dissipative in \( \tilde{X}_1 \). The rest of the proof follows from Theorem 7.1. \( \square \)

**Remark 7.7.** As we shall see in Section 8, 0 actually does not belong to \( \sigma(-\tilde{A}_1) \).

We denote by \( P_1 \) the orthogonal projection in \( L^2(\Omega) \) onto \( Z_T(\Omega) \).

**Lemma 7.8.** Let \( U_0 \in X_1 \) and \( U \) be the solution of problem (32). It holds that

\[
P_1(B(t)) = P_1(B_0), \quad \forall t > 0. \tag{123}
\]

*Proof.** Just multiply Equation (13) by a element of \( Z_T(\Omega) \) and integrate by parts on \( \Omega \). \( \square \)

Lemma 7.8 shows that the projection of the solution \( U \) onto \( \ker(\tilde{A}_1; X_1) \) does not depend on the time. Then we conclude...

**Corollary 7.9.** It holds that

\[
\lim_{t \to +\infty} \left\| T_1(t)U_0 - \sum_{1 \leq j \leq J} \xi_j(0, 0, 0, \text{grad} \tilde{q}_j)^\top \right\|_{X_1} = 0, \quad \forall U_0 \in X_1,
\]
where \( \xi_j = (B_0 \cdot n, 1)_{\Sigma_j} \), for \( j = 1, \ldots, J \).

**Proof.** Let \( U_0 \in X_1 \). From the orthogonal decomposition (94) and Lemma 7.8, we deduce that the solution \( U \) to the system (10)–(14) and (9), with boundary conditions (15) and (17), can be written as:

\[
U(t) = \tilde{U}(t) + (0, 0, 0, P_1 B_0),
\]

and \( \tilde{U}(t) \in \tilde{X}_1 \) is the solution of problem

\[
\partial_t \tilde{U}(t) + \tilde{A}_1 \tilde{U}(t) = 0, \quad t > 0, \quad \tilde{U}(0) = \tilde{U}_0,
\]

where the initial condition \( \tilde{U}_0 = U_0 - (0, 0, 0, P_1 B_0) \) belongs to \( \tilde{X}_1 \). Next, let \( \xi_j, j = 1, \ldots, J \) be a constants such that \( P_1 B_0 = \sum_{1 \leq j \leq J} \xi_j \langle \text{grad} \dot{q}_j \cdot n, 1 \rangle_{\Sigma_i} \). Therefore, \( B_0 - P_1 B_0 \) belongs to \( H^1_0(\text{div} 0; \Omega) \), which yields:

\[
\langle B_0 \cdot n, 1 \rangle_{\Sigma_i} = \sum_j \xi_j \langle \text{grad} \dot{q}_j \cdot n, 1 \rangle_{\Sigma_i} = \xi_i.
\]

Finally, from Theorem 7.6, \( \tilde{U} \) satisfies \( \lim_{t \to +\infty} \| \tilde{U}(t) \|_{\tilde{X}_1} = 0 \), hence the result. \( \square \)

### 7.2. Homogeneous Silver–Müller case

**Proposition 7.10.** For all \( \alpha \in \mathbb{R} \setminus \{0\} \), the operator \( i \alpha I + A_2 \) is injective, i.e.,

\[
\ker(i \alpha I + A_2) = \{0\}.
\]

Furthermore, 0 is an eigenvalue of \( A_2 \) and the set of its eigenvectors is

\[
\ker(A_2) = \{(0, 0, 0, V) : V \in H_{0,\Gamma_A}(\text{curl} 0; \Omega)\}.
\]

**Proof.** Let \( \alpha \in \mathbb{R} \) and \( U = (U_1, U_2, U_3, U_4)^{\top} \in D(A_2) \) be such that

\[
(i \alpha I + A_2) U = 0,
\]

which is equivalent, in \( \Omega \), to the system (86)–(89). Taking the inner product of (124) with \( U \), one gets:

\[
\Re(i \alpha \| U \|_{\tilde{X}}^2) = \Re(A_2 U \mid U)_{X} = 0.
\]

By the monotonicity of \( A_2 \), see (53), one obtains

\[
\left( \frac{\nu_s U_s}{\varepsilon_0 \omega_{ps}} \right) \left( \frac{U_s}{\omega_{ps}} \right) = 0, \quad s = 1, 2, \quad \text{and} \quad \| U_4 \|_{L^2(\Gamma_A)} = 0.
\]

The rest of the proof follows the same arguments as Proposition 7.2. \( \square \)

The above Proposition states that \( \ker A_2 \) coincides with the set of stationary solutions to the problem (10)–(14) with boundary condition (15) and (16) (with \( g = 0 \)). Similarly to the operator \( A_1 \), if we define the operator \( A_2 |_{X_2} : D(A_2) \cap X_2 \to X_2 \) as the restriction of \( A_2 \) to the space \( X_2 \), then we obtain

\[
\ker(A_2 |_{X_2}) = \{0\}^3 \times Z(\Omega; \Gamma_A),
\]
where the kernel
\[ Z(Ω; Γ_0) := H_{0,Γ,0}(\text{curl} 0; Ω) \cap H_{0,Γ,0}(\text{div} 0; Ω). \]

Note that the set of stationary solution to Equations (10)–(14) and (9), with boundary conditions (15)–(17) and \( g = 0 \), is equal to \( \ker(Δ_2|X_2) \).

The space \( Z(Ω; Γ_0) \) has been studied by Fernandes and Gilardi in [12]. It is of finite dimension and from [12, Corollary 5.2] one has \( \dim Z(Ω; Γ_0) \leq N + J - 1 \). (We recall that \( N \) is the number of connected components of \( Γ_0 \).)

We now recall some orthogonal decompositions from [12]; we mostly keep the same notations. Picking a vector \( a \in \mathbb{R}^N \) such that \( \sum_{i=1}^{N} a_i \neq 0 \), we define the space \( H^2_{\text{const}}(Γ, Ω; a) := \{ p \in H^2(Γ) : \exists c \in \mathbb{R}^N, \exists c' \in \mathbb{R}^J : c \cdot a = 0, p|Γ_i = c_i \text{ for } i = 1, \ldots, N; [p]|_{Σ_j} = c'_j \text{ for } j = 1, \ldots, J \} \). Moreover we introduce
\[ H_{0,Γ,0}(\text{div} 0; Ω) := \{ v \in H_{0,Γ,0}(\text{div} 0; Ω) : \langle v \cdot n, p \rangle_{H^2(Γ; Ω)} = 0 \ \forall p \in H^2_{\text{const}}(Γ, Ω; a) \}. \]

For the proof, we refer the reader to [12, Proposition 3.3 and Remark 2.1]. Then, we have the orthogonal decompositions in \( L^2(Ω) \) which are proven in [12, Propositions 6.3 and 6.4]:
\[ H_{0,Γ,0}(\text{div} 0; Ω) = Z(Ω; Γ_0) \downarrow \downarrow H_{0,Γ,0}(\text{div} 0; Ω), \]
\[ L^2(Ω) = H_{0,Γ,0}(\text{curl} 0; Ω) \downarrow \downarrow H_{0,Γ,0}(\text{div} 0; Ω). \]

**Proposition 7.11.** For all \( α \in \mathbb{R} \setminus \{ 0 \} \), the operator \( iαI + A_2 \) is surjective, i.e.
\[ \text{im } (iαI + A_2) = X. \]

**Proof.** We follow the lines of the proof of Proposition 7.3. Let \( α \in \mathbb{R} \setminus \{ 0 \} \) and \( F = (F_1, F_2, F_3, F_4)^T \in X \); we look for \( U = (U_1, U_2, U_3, U_4)^T \in D(A_2) \) which solves:
\[ (iαI + A_2) U = F, \]
which is equivalent to the system (97)–(100), with different boundary conditions. Again, we eliminate \( U_1, U_2 \) and \( U_4 \) by (101), (102) and (103) respectively, while \( U_3 \) verifies the equation (104) in \( Ω \). Given the Silver–Müller boundary condition, the mixed formulation of (104) writes — recall the space \( V \) from (51):
**Find** \( (U_3, p) \in V \times H^1_{\text{div}}(Ω) \) **such that**
\[ \tilde{α}_α(U_3, v) + c_α(U_3, v) + b_α(v, p) = L_α(v), \quad ∀v \in V, \]
\[ b_α(u_3, q) = (G | \text{grad } q), \quad ∀q \in H^1_{\text{div}}(Ω), \]
where the sesquilinear form \( \tilde{α}_α \) is defined on \( V \times V \) as:
\[ \tilde{α}_α(w, v) := α_α(w, v) + c_α(w \cdot v), \quad ∀w, v \in Γ_A. \]
the form \( a_\alpha \) being defined in (107); on the other hand, \( b_\alpha, c_\alpha, L_\alpha \) are as in (108)–(110), except that the variable \( v \) now belongs to \( \mathcal{V} \). Again, \( G \) is an element of \( L^2(\Omega) \) which will be chosen later.

Checking the hypotheses of [3, Theorem 4.5.9] proceeds as in Proposition 7.3.

i) **Continuity:** obvious.

ii) **Coercivity on the kernel:** the kernel of \( b_\alpha(\cdot, \cdot) \) is defined by

\[
K = \{ v \in \mathcal{V} : b_\alpha(v, q) = 0, \quad \forall q \in H^1_0(\Omega) \}
\]

which, by the Green formulas (68) and (67), can be written as:

\[
K = \{ v \in \mathcal{V} \cap H(\text{div}, \Omega) : (\mathbb{B}_\alpha v \cdot n, 1)_{H^{1/2}(\Gamma_A)} = 0, \quad \forall 1 \leq k \leq K \}
= \{ v \in \mathcal{V} \cap H(\text{div}, \Omega) : P_{Z_N(\Omega; \mathbb{B}_\alpha)} v = 0 \}.
\]

This kernel is compactly embedded into \( L^2(\Omega) \) by Theorem 5.6. Furthermore, according to Corollary 5.8, the sesquilinear form \( \tilde{a}_\alpha \) is coercive on \( K \times K \). Indeed, taking \( v \in K \), we find

\[
|\tilde{a}_\alpha(v, v)| = \left| (\alpha)^{-1}c^2 \| \text{curl} v \|^2 + c \| v_T \|^2_{L^2(\Gamma_A)} \right| = \left( (|\alpha|^{-1}c^2 \| \text{curl} v \|^2)^2 + (c \| v_T \|^2_{L^2(\Gamma_A)})^2 \right)^{1/2}.
\]

But, we have the inequality

\[
(z^2 + y^2)^{1/2} \geq \frac{1}{\sqrt{2}} |z + y|, \quad \forall (z, y) \in \mathbb{R}^2.
\]

Consequently,

\[
|\tilde{a}_\alpha(v, v)| \geq \frac{1}{\sqrt{2}} \left( |\alpha|^{-1}c^2 \| \text{curl} v \|^2 + c \| v_T \|^2_{L^2(\Gamma_A)} \right)
\geq \frac{1}{\sqrt{2}} \min\{|\alpha|^{-1}c^2, c\} \left( \| \text{curl} v \|^2 + \| v_T \|^2_{L^2(\Gamma_A)} \right) = C \| v \|^2_{X_N; r(\Omega; \mathbb{B}_\alpha)}.
\]

iii) **Inf-sup condition:** take any \( q \in H^1_0(\Omega) \) and set \( v = \text{grad} q \). Then, we have \( \text{curl} v = 0 \in L^2(\Omega) \) and \( v_T = 0 \in L^2(\Gamma) \), thus \( v \in \mathcal{V} \) and verifies \( \| v \|_{\mathcal{V}} = \| v \| \). The conclusion follows from the inequalities (111) and (112).

As in the perfect conductor case, we can apply the Fredholm alternative. So, we show that the variational formulation (128) is injective on the kernel. Let \( Z_3 \) be a solution to the variational formulation

\[
\forall v \in K, \quad \tilde{a}_\alpha(Z_3, v) + c_\alpha(Z_3, v) = 0.
\]

(131)

Since \( Z_3 \) belongs to \( K \), one has \( Z_3 \in H(\text{curl}; \Omega) \) with \( \text{div} \mathbb{B}_\alpha Z_3 = 0 \) in \( \Omega \) and \( Z_3 \times n|_{\Gamma_p} = 0 \). As in Proposition 7.3, we obtain the existence of \( Z_1, Z_2 \in L^2(\Omega) \) and \( Z_4 \in H(\text{curl}; \Omega) \) such that \( (i\omega + k)Z = 0 \), with \( Z = (Z_1, Z_2, Z_3, Z_4)^T \). To apply Proposition 7.10, we must check that \( Z \in D(k_2) \), i.e., the Silver–Müller condition is satisfied. For \( v \in K \), using the integration-by-parts formula (19) in (131) and Equation (114), we get

\[
(Z_3 \times v_T)_{\Gamma_A} - c_{\gamma_A} \langle Z_4 \times n, v_T \rangle_{\Sigma_A} = 0, \quad \forall v \in K.
\]

(132)

Now, consider any \( y \in \mathcal{V} \). Let \( \varphi \) be the unique element of \( H^1_0(\Omega) \) such that

\[
(\mathbb{B}_\alpha \text{grad} \varphi | \text{grad} \psi) = (\mathbb{B}_\alpha y | \text{grad} \psi), \quad \forall \psi \in H^1_0(\Omega).
\]
So, \(v := y - \nabla \varphi\) belongs to \(K\) with \(v_{\Gamma} = y_{\Gamma}\) on \(\Gamma_A\). Using it as a test function in (132), we find
\[
(Z_{3\Gamma} | y_{\Gamma})_{\Gamma_A} - c\gamma_A (Z_4 \times n, y_{\Gamma})_{\Sigma_A^0} = 0, \quad \forall y \in \mathcal{V}.
\]
The above equation is the same as (57), thus we obtain the Silver–Müller boundary condition as in the proof of Proposition 4.7. Consequently, \(Z\) belongs to \(D(\tilde{A}_2)\), and from Proposition 7.10 we infer that \(Z = 0\), so \(Z_3 = 0\): the formulation (131) is injective.

We deduce by Theorem 4.5.9 and Proposition 4.5.8 of [3] that the problem (128)–(129) admits a unique solution \((U_3, p) \in \mathcal{V} \times H^1_{\partial \Omega}(\Omega)\). Choosing \(G\) as in (118), we get once again \(p = 0\). Thus, \(U_3\) satisfies (104), or equivalently
\[
\frac{c^2}{i\alpha} \text{curl(curl)} U_3 - F_4 = \mathbb{B}_0 U_3 = F_3 - \frac{1}{\varepsilon_0} \sum_s (i\omega I + \mathbb{M}_s)^{-1} F_s
\]
in the sense of distributions. Defining \(U_1, U_2, U_4\) respectively by (101), (102), and (103), these fields clearly belong to \(L^2(\Omega)\). Combining (133) and (103) with the definition of \(\mathbb{B}_0\), one sees that \(U_4 \in H(\text{curl}; \Omega)\). Thus, the quadruple \((U_1, U_2, U_3, U_4)\) verifies the system (97)–(100). For this quadruple to belong to \(D(\tilde{A}_2)\), we have to check that the Silver–Müller condition holds. To this end, we use the Green formula (19) in (128), and find that
\[
c(U_3 \gamma | v_{\Gamma})_{\Gamma_A} - c^2 \gamma_A (U_4 \times n, v_{\Gamma})_{\Sigma_A^0} = 0, \quad \forall v \in \mathcal{V}.
\]
Following the same argument as in the proof of Proposition 4.7, we deduce that Equation (134) implies that \(U_{3\Gamma} - c U_4 \times n = 0\) in \(H^{-\frac{1}{2}}(\Gamma_A)\) which is equivalent to \(U_3 \times n + c U_4 = 0\) in \(H^{-\frac{1}{2}}(\Gamma_A)\) and thus in \(L^2(\Gamma_A)\) because \(U_{3\Gamma}\) belongs to \(L^2(\Gamma_A)\). The proof is complete.

Let us introduce yet another closed subspace of \(\tilde{X}\):
\[
\tilde{X}_2 := L^2(\Omega) \times L^2(\Omega) \times L^2(\Omega) \times H_{0,\Gamma^p,\text{flux},\Gamma_A,\Sigma}(\text{div}; \Omega).
\]
It is a Hilbert space when endowed with the inner product of \(\tilde{X}\).

**Proposition 7.12.** The range \(im(\tilde{A}_2)\) of \(\tilde{A}_2\) is included in \(\tilde{X}_2\).

**Proof.** Let \(U = (U_1, U_2, U_3, U_4)^t\) be an element of \(D(\tilde{A}_2)\). Then, by the definition (49) of \(\tilde{A}_2\), \(\tilde{A}_2 U\) belongs to \(\tilde{X}_2\) if, and only if, \(\text{curl} U_3\) belongs to \(H_{0,\Gamma^p,\text{flux},\Gamma_A,\Sigma}(\text{div}; \Omega)\). Recall that \(U_3\) belongs to \(H_{0,\Gamma^p}(\text{curl}; \Omega)\), therefore one can conclude by [12, Lemma 7.7].

The results of the spectral analysis of the operator \(\tilde{A}_2\) lead us to introduce the unbounded operator \((D(\tilde{\tilde{A}}_2), \tilde{\tilde{A}}_2)\) on \(\tilde{X}_2\) defined by
\[
D(\tilde{\tilde{A}}_2) = D(\tilde{A}_2) \cap \tilde{X}_2 \quad \text{and} \quad \tilde{\tilde{A}}_2 U = \tilde{A}_2 U, \quad \forall U \in D(\tilde{A}_2).
\]

**Proposition 7.13.** For all \(\alpha \in \mathbb{R}\), the operator \(i\alpha I + \tilde{\tilde{A}}_2\) is surjective. For \(\alpha \in \mathbb{R} \setminus \{0\}\), it is injective.

**Proof.** Similar to Proposition 7.5, using Propositions 7.10, 7.11, 7.12, and the orthogonal decomposition (126).

Observe that \(\tilde{X}_2\) is an invariant space for Problem (50), see Lemma 7.15. We define \(\tilde{T}_2 := \tilde{T}_2|_{D(\tilde{\tilde{A}}_2) \cap \tilde{X}_2}\).

**Theorem 7.14.** The semigroup of contractions \((\tilde{T}_2(t))_{t \geq 0}\) with generator \(-\tilde{\tilde{A}}_2\) is strongly stable on the energy space \(\tilde{X}_2\) in the sense that
\[
\lim_{t \to +\infty} \| \tilde{T}_2(t) \tilde{U}_0 \|_{\tilde{X}} = 0, \quad \forall \tilde{U}_0 \in \tilde{X}_2.
\]

**Proof.** It is sufficient to repeat the proof of Theorem 7.6.

We denote by \(P_2\) the orthogonal projection in \(L^2(\Omega)\) onto \(Z(\Omega; \Gamma_A)\).
Lemma 7.15. Let $U_0 \in X_2$ and $U$ is the solution of problem (50). It holds that

$$P_2(B(t)) = P_2(B_0), \quad \forall t > 0.$$ 

Combining this result with Theorem 7.14, we conclude

Corollary 7.16. It holds that

$$\lim_{t \to +\infty} \| T_2(t)U_0 - (0, 0, 0, P_2B_0)^\top \|_{X_2} = 0, \quad \forall U_0 \in X_2.$$ 

8. Stronger stability

We now establish explicit decay rates (polynomial or exponential) for the energy. Our results are based on theorems relating the decay of the resolvent of an operator with respect to frequency and the decay of the generated semigroup with respect to time.

Namely, exponential decay will be derived from the following Theorem [14, 21]:

Theorem 8.1 (Pruß / Huang). A $C^0$-semigroup $(T(t))_{t \geq 0}$ of contractions on a Hilbert space $X$ generated by $L$ is exponentially stable, i.e., it satisfies

$$\forall t \geq 0, \quad \forall u_0 \in X, \quad \| T(t)u_0\| \leq Ce^{-\gamma t}\|u_0\|_X,$$

for some positive constants $C$ and $\gamma$ if, and only if,

$$i\mathbb{R} = \{i\beta : \beta \in \mathbb{R}\} \subset \rho(L),$$

the resolvent set of the operator $L$, and

$$\sup_{\beta \in \mathbb{R}} \| (i\beta I - \mathcal{L})^{-1} \| < +\infty.$$ 

On the other hand, polynomial decay will follow from this other one [6, Theorem 2.4]:

Theorem 8.2. A $C^0$-semigroup $(T(t))_{t \geq 0}$ of contractions on a Hilbert space $X$ generated by $\mathcal{L}$ satisfies

$$\forall t > 1, \quad \forall u_0 \in D(\mathcal{L}), \quad \| T(t)u_0\| \leq Ct^{-\frac{1}{2}}\|u_0\|_{D(\mathcal{L})},$$

as well as

$$\forall t > 1, \quad \forall u_0 \in D(\mathcal{L}^\ell), \quad \| T(t)u_0\| \leq Ct^{-1}\|u_0\|_{D(\mathcal{L}^\ell)},$$

for some constant $C > 0$ and for some positive integer $\ell$ if (137) holds and if

$$\limsup_{|\beta| \to \infty} \frac{1}{|\beta|^\ell} \| (i\beta I - \mathcal{L})^{-1} \| < +\infty.$$ 

8.1. Polynomial stability, perfectly conducting case

Proposition 8.3. Let $\rho(-\tilde{\mathcal{A}}_1)$ denote the resolvent set of $-\tilde{\mathcal{A}}_1$. Then, $0 \in \rho(-\tilde{\mathcal{A}}_1)$.

Proof. By Proposition 7.5, we know that $0 \in i\mathbb{R}$ is not an eigenvalue, so in order to prove that $0 \in \rho(-\tilde{\mathcal{A}}_1)$, we need to check that $\tilde{\mathcal{A}}_1$ is surjective and has a bounded inverse. Both properties follow from the fact that the resolvent of $-\tilde{\mathcal{A}}_1$ is uniformly bounded in the neighborhood of 0, which we shall now prove by a contradiction argument.
Suppose the above condition is false, then there exists a sequence \((\beta_n)_{n \in \mathbb{N}}\) on \(\mathbb{R} \setminus \{0\}\) with \(\beta_n \to 0\) as \(n \to +\infty\), and a sequence of vector fields \((U^n)_{n \in \mathbb{N}} = (\begin{pmatrix} U_1^n, U_2^n, U_3^n, U_4^n \end{pmatrix})_n\) on \(D(\hat{A}_1)\), with
\[
\|U^n\|_X = 1, \quad \forall n,
\]
such that
\[
\|(i\beta_n I + \hat{A}_1) U^n\|_X \to 0 \quad \text{as} \quad n \to +\infty,
\]
which is equivalent to
\[
\begin{align*}
  i\beta_n U_1^n + M_2 U_1^n + \varepsilon_0 \omega_0^2 U_3^n & \to 0 \quad \text{in} \quad L^2(\Omega), \\
  i\beta_n U_2^n + M_2 U_2^n + \varepsilon_0 \omega_0^2 U_3^n & \to 0 \quad \text{in} \quad L^2(\Omega), \\
  \varepsilon_0 \omega_0^2 \beta_n U_3^n + U_1^n + U_2^n + \varepsilon_0 c^2 \text{curl} U_4^n & \to 0 \quad \text{in} \quad L^2(\Omega), \\
  \varepsilon_0 c^2 \beta_n U_4^n + \varepsilon_0 c^2 \text{curl} U_3^n & \to 0 \quad \text{in} \quad L^2(\Omega).
\end{align*}
\]

Since, by (35) and (140),
\[
\sum_s \frac{\nu_s U^n_s}{n_0 \omega_p s} \left|\frac{U^n_s}{\omega_p s}\right| = \Re((i\beta_n I + \hat{A}_1) U^n, U^n)_X \leq \|(i\beta_n I + \hat{A}_1) U^n\|_X,
\]
we obtain from (141) that
\[
\left(\frac{\nu_s U^n_s}{n_0 \omega_p s} \mid \frac{U^n_s}{\omega_p s}\right) \to 0, \quad \text{as} \quad n \to +\infty, \quad s = 1, 2
\]
which leads by (91) to
\[
\|U^n_s\|_{(s)} \to 0, \quad \text{as} \quad n \to +\infty, \quad s = 1, 2.
\]
The matrix \(M_s\) is bounded on \(\Omega\), so it follows from to (148) and (142) that
\[
U^n_3 \to 0 \quad \text{in} \quad L^2(\Omega), \quad \text{as} \quad n \to +\infty
\]
and then we deduce from (144) that
\[
\text{curl} U^n_4 \to 0 \quad \text{in} \quad L^2(\Omega), \quad \text{as} \quad n \to +\infty.
\]
This shows that \((\text{curl} U^n_4)_n\) is bounded in \(L^2(\Omega)\). Taking account of (140), the sequence \((U^n_4)_n\) is bounded in \(H(\text{curl}; \Omega)\), and more specifically in the closed subspace \(J_1(\Omega) := H(\text{curl}; \Omega) \cap H_0^2(\text{div}; \Omega)\) to which all its terms belong given the definition of \(D(\hat{A}_1)\), see (121) and (120). But \(J_1(\Omega)\) is also a closed subspace of \(H(\text{curl}; \Omega) \cap H_0^2(\text{div}; \Omega)\), which is compactly embedded into \(L^2(\Omega)\) [3, Theorem 3.5.4]; thus, we can extract a subsequence still denoted by \((U^n_4)_n\), which converges strongly in \(L^2(\Omega)\) to some \(U_4 \in J_1(\Omega)\). As a consequence, \((\text{curl} U^n_4)_n\) converges in the sense of distributions to \(\text{curl} U_4\); this combined with (150) implies that
\[
\text{curl} U^n_4 \to \text{curl} U_4 = 0 \quad \text{in} \quad L^2(\Omega), \quad \text{as} \quad n \to +\infty.
\]
So, \(U_4 \in H(\text{curl}; \Omega)\). Together with \(U_4 \in J_1(\Omega)\), this means that \(U_4\) belongs to \(Z_T(\Omega) = H(\text{curl}; 0; \Omega) \cap H_0^2(\text{div}; \Omega)\) and its orthogonal \(H_T^2(\text{div}; 0; \Omega)\) (cf. (94)), whence \(U_4 = 0\).

On the other hand, (140), (148) and (149) imply that
\[
1 = \lim_{n \to +\infty} \|U^n\|_X^2 = \lim_{n \to +\infty} \varepsilon_0 c^2 \|U^n_4\|^2 = \varepsilon_0 c^2 \|U_4\|^2,
\]
in particular, $U_k ≠ 0$, and the above conclusion is contradicted. Hence the resolvent is uniformly bounded in the neighborhood of 0:

$$\exists C > 0, \forall \beta ∈ [-1,1] \setminus \{0\}, \quad \| (i\beta I + \tilde{A}_1)^{-1} \| ≤ C.$$  \hfill (151)

The surjectivity of $\tilde{A}_1$ and the boundedness of its inverse then follow from a standard argument. Pick any $F ∈ \tilde{X}_1$. By Proposition 7.5, for any $k ∈ N \setminus \{0\}$ there exists a unique $U^k ∈ D(\tilde{A}_1)$ such that $(ik^{-1} + \tilde{A}_1)U^k = -F$, and $\|U^k\|_X ≤ C\|F\|_X$.

Being bounded, the sequence $(U^k)_k$ admits a subsequence (still denoted $(U^k)_k$) that converges weakly toward $U ∈ \tilde{X}_1$, as the latter is a closed subspace of $X$, which still satisfies $\|U\|_X ≤ C\|F\|_X$. Moreover, $-\tilde{A}U^k → -\tilde{A}U$ in the sense of distributions. But, on the other hand

$$-\tilde{A}U^k = F + ik^{-1}U^k → F \quad \text{in } X.$$

Hence, $-\tilde{A}U = F$, i.e., $U ∈ D(\tilde{A}_1)$. As $F$ is arbitrary, this proves that $-\tilde{A}_1$ is surjective, hence bijective, between $D(\tilde{A}_1)$ and $\tilde{X}_1$, and its inverse is bounded: $\|(-\tilde{A}_1)^{-1}\| ≤ C$ and $\|(-\tilde{A}_1)^{-1}\|_{\tilde{X}_1 → D(\tilde{A}_1)} ≤ C + 1$. \hfill □

**Remark 8.4.** The surjectivity of $-\tilde{A}_1$ could have been easily obtained by a direct argument. We gave this proof because it provides a pattern for subsequent ones.

**Proposition 8.5.** The resolvent of the operator $-\tilde{A}_1$ satisfies the condition (139) with $ℓ = 2$.

**Proof.** We again use a contradiction argument, i.e., we assume that (139) is false for some $⃗{ℓ} ∈ N$, which will be specified later. Then, there exists a sequence $(\beta_n)_n ∈ N$ on $\mathbb{R}$ with $|\beta_n| → +∞$ as $n → +∞$, and a sequence $(U^n)_n ∈ N = (U^n_1, U^n_2, U^n_3)$. Of elements of $D(\tilde{A}_1)$, such that

$$\|U^n\|_X = 1, \quad \forall n,$$

and

$$|\beta_n|^\ell \|(i\beta_nI + A_1)U^n\|_X → 0 \quad \text{as } n → +∞,$$  \hfill (153)

which is equivalent to

$$\beta_n^\ell (i\beta_n U^n_1 + M_1 U^n_1 - \varepsilon_0\omega_p^2 U^n_3) \rightarrow 0 \quad \text{in } L^2(Ω),$$  \hfill (154)

$$\beta_n^\ell (i\beta_n U^n_2 + M_2 U^n_2 - \varepsilon_0\omega_p^2 U^n_3) \rightarrow 0 \quad \text{in } L^2(Ω),$$  \hfill (155)

$$\beta_n^\ell (i\varepsilon_0^2\beta_n U^n_4 + U^n_1 + U^n_2 - \varepsilon_0^2 \text{curl}U^n_3) \rightarrow 0 \quad \text{in } L^2(Ω),$$  \hfill (156)

$$\beta_n^\ell (i\varepsilon_0^2\beta_n U^n_4 + \varepsilon_0^2 \text{curl}U^n_3) \rightarrow 0 \quad \text{in } L^2(Ω).$$  \hfill (157)

As, according to (35) and (152),

$$|\beta_n^\ell|^\ell \sum_s (\nu_s U^n_s \left| \frac{\nabla \nu_n}{\omega_p} \right| U^n_s) = |\beta_n^\ell| |\Re((i\beta_nI + A_1)U^n, U^n)|_X ≤ |\beta_n^\ell|^\ell \|(i\beta_nI + A_1)U^n\|_X,$$  \hfill (158)

we infer from (153) that

$$|\beta_n^\ell|^\ell \left( \frac{\nu_s U^n_s}{\varepsilon_0^2\omega_p} \left| \frac{\nabla \nu_n}{\omega_p} \right| U^n_s \right) → 0 \quad \text{as } n → +∞, \quad s = 1, 2,$$

which implies, by Hypotheses 1 and 2,

$$\beta_n^\ell U^n_s → 0 \quad \text{in } L^2(Ω), \quad \text{as } n → +∞, \quad s = 1, 2.$$

\hfill (159)
(For the sake of simplicity, one may assume \( \ell \) even, so that \( \beta_n^{\ell/2} \) is unambiguously defined; otherwise, one may choose a principal determination for the square root of a negative real number. This is of little importance, as all the limits we consider are zero.)

Multiplying (154) by \( \beta_n^{-\ell/2-1} \), we get:

\[
i\beta_n^{\ell/2} U_1^n + \beta_n^{-\ell/2-1} M_1 U_1^n - \varepsilon_0 \omega_2^2 \beta_n^{-\ell/2-1} U_3^n \to 0 \quad \text{in } L^2(\Omega),
\]
together with (159), this yields

\[
\beta_n^{\ell/2-1} U_3^n \to 0, \quad \text{in } L^2(\Omega) \quad \text{as } n \to +\infty. \tag{160}
\]

Similarly, multiplying (156) by \( \beta_n^{-\ell/2-2} \) yields:

\[
i\beta_n^{\ell/2-1} \varepsilon_0 U_3^n + \beta_n^{\ell/2-2} U_1^n + \beta_n^{\ell/2-2} U_2^n - \varepsilon_0 c^2 \beta_n^{\ell/2-2} \text{curl} U_4^n \to 0 \quad \text{in } L^2(\Omega),
\]
taking (159) and (160) into account, we arrive at:

\[
\beta_n^{\ell/2-2} \text{curl} U_4^n \to 0 \quad \text{in } L^2(\Omega), \quad \text{as } n \to +\infty. \tag{161}
\]

Now, let us multiply (157) by \( \beta_n^{-\ell/2-2} \):

\[
i\varepsilon_0 c^2 \beta_n^{\ell/2-1} U_4^n + \varepsilon_0 c^2 \beta_n^{\ell/2-2} \text{curl} U_3^n \to 0 \quad \text{in } L^2(\Omega),
\]
then we take the inner product (on the right side) of this equation by \( U_4^n \) and find

\[
i\varepsilon_0 c^2 \beta_n^{\ell/2-1} \|U_4^n\|^2 + \varepsilon_0 c^2 \beta_n^{\ell/2-2} (\text{curl} U_3^n \mid U_4^n) \to 0, \quad \text{as } n \to +\infty. \tag{162}
\]

On the other hand, using the Green formula (18) and the condition \( U_3^n \times n = 0 \) on \( \Gamma \), we obtain:

\[
\beta_n^{\ell/2-2} (\text{curl} U_3^n \mid U_4^n) = (U_3^n \mid \beta_n^{\ell/2-2} \text{curl} U_4^n) \leq \|U_3^n\| \|\beta_n^{\ell/2-2} \text{curl} U_4^n\|.
\]

Assuming \( \ell \geq 2 \), we deduce from (160) that:

\[
\|U_3^n\| \to 0, \quad \text{as } n \to +\infty. \tag{163}
\]

Thus, from Equations (163), (164) and (161), we deduce

\[
\beta_n^{\ell/2-2} (\text{curl} U_3^n \mid U_4^n) \to 0, \quad \text{as } n \to +\infty. \tag{165}
\]

Together with (162), the latter property implies

\[
\beta_n^{\ell/2-1} \|U_4^n\|^2 \to 0, \quad \text{as } n \to +\infty \tag{166}
\]

if \( \ell \geq 2 \). In this case, the exponent \( \frac{\ell}{2} - 1 \geq 0 \), and there holds \emph{a fortiori}:

\[
\|U_4^n\| \to 0, \quad \text{as } n \to +\infty. \tag{167}
\]

As (159) implies, for all \( \ell > 0 \), that

\[
\|U_s^n\| \to 0, \quad \text{as } n \to +\infty, \quad s = 1, 2, \tag{168}
\]
taking (164) and (167) into account and using the equivalence of norms, we obtain \( \|U^n\|_X \to 0 \) as \( n \to +\infty \), which contradicts (152).

Hence, according to Theorem 8.2 we conclude.

**Theorem 8.6.** The semigroup of contractions \( \{\tilde{T}_t(t)\}_{t\geq 0} \), with generator \(-\tilde{\Lambda}_1\), is polynomially stable on \( \mathcal{X}_1 \), i.e., there exist a constant \( C > 0 \) such that

\[
\forall t > 1, \quad \|\tilde{T}_t(t)\tilde{U}_0\|_{\tilde{\mathcal{X}}_1} \leq C t^{-\frac{1}{2}} \|\tilde{U}_0\|_{D(\tilde{\Lambda}_1)}, \quad \forall \tilde{U}_0 \in D(\tilde{\Lambda}_1).
\]

(169)

Furthermore, under the assumptions of Theorem 4.10 on \( B_0 \), there exists a constant \( M > 0 \) such that the solution to Problem (32) taking (164) and (167) into account and using the equivalence of norms, we obtain

\[
\beta \text{ is uniformly bounded in the neighborhood of } 0 \text{ by using a contradiction argument. Suppose it is not the case,}
\]

we follow the same argument in the proof of Proposition 8.3, and we prove that the resolvent of

\[
\text{Proof. Equation (170) is a consequence of (169) and Corollary 7.9.}
\]

\[\square\]

\section{8.2. Polynomial stability, homogeneous Silver–Müller case}

**Proposition 8.7.** Let \( \rho(-\tilde{\Lambda}_2) \) denote the resolvent set of \(-\tilde{\Lambda}_2\). Then, \( 0 \in \rho(-\tilde{\Lambda}_2) \).

Proof. We follow the same argument in the proof of Proposition 8.3, and we prove that the resolvent of \(-\tilde{\Lambda}_2\) is uniformly bounded in the neighborhood of 0 by using a contradiction argument. Suppose it is not the case, then there exists a sequence \( (\beta_n)_{n \in \mathbb{N}} \) on \( \mathbb{R} \setminus \{0\} \) with \( \beta_n \to 0 \) as \( n \to +\infty \), and a sequence of vectors fields \( (U^n)_{n \in \mathbb{N}} = ((U^n_1, U^n_2, U^n_3, U^n_4)^T)_{n} \) on \( D(\tilde{\Lambda}_2) \), with

\[
\|U^n\|_X = 1, \quad \forall n,
\]

(171)

such that

\[
\|(i\beta_n\mathbf{I} + \tilde{A}_2)U^n\|_X \to 0 \quad \text{as } n \to +\infty,
\]

(172)

this again implies the system (142)–(145), with different boundary conditions.

By the monotonicity of \( \Lambda_2 \) (Equation (53)) and (171):

\[
\sum_s \left( \frac{\mu_s U^n_s}{\varepsilon_0 \omega_{ps}} \right) \left( \frac{U^n_s}{\omega_{ps}} \right) + \varepsilon_0 c^\beta \|U^n_{4T}\|_{L^2(\Gamma_A)}^2 = \Re \left( \langle (i\beta_n\mathbf{I} + \tilde{A}_2)U^n, U^n \rangle_X \right) \leq \|(i\beta_n\mathbf{I} + \tilde{A}_2)U^n\|_X,
\]

we obtain from (172)

\[
\left( \frac{\mu_s U^n_s}{\varepsilon_0 \omega_{ps}} \right) \left( \frac{U^n_s}{\omega_{ps}} \right) \to 0, \quad \text{as } n \to +\infty \quad \forall s = 1, 2
\]

(173)

and

\[
\|U^n_{4T}\|_{L^2(\Gamma_A)}^2 \to 0, \quad \text{as } n \to +\infty.
\]

(174)

As already said, the condition \( U^n_{4T} \in L^2(\Gamma_A) \) follows from the Silver–Müller boundary condition, in the absence of pathological vertices.
we infer from (178) that:

\[ A \]

Again, the latter condition is equivalent to the system (154)–(157), with different boundary conditions.

The resolvent of the operator \( U \) in particular,

\[ H \]

Proof. \[ H \]

weak convergence in \( J \)

denoted (\( \cdot \)) which is compactly embedded into \( L \)

Hence, (\( \cdot \)) also appears as a closed subspace of

\[ W \cap \mathcal{H} \]

Yet, \( \mathcal{J}_{2}(\Omega) \) also appears as a closed subspace of

\[ \left\{ w \in \mathcal{H}(\text{curl};\Omega) \cap \mathcal{H}(\text{div};\Omega) : w \cdot n_{|\Gamma_{p}} \in L^{2}(\Gamma_{p}) \text{ and } w \times n_{|\Gamma_{A}} \in L^{2}(\Gamma_{A}) \right\} , \]

which is compactly embedded into \( L^{2}(\Omega) \) [12, Proposition 7.3]. Therefore, we can extract a subsequence, still denoted (\( U_{n}^{4} \))\(_{n}\), which converges strongly in \( L^{2}(\Omega) \), and weakly in \( \mathcal{J}_{2}(\Omega) \), to some \( U_{4} \in \mathcal{J}_{2}(\Omega) \). Combining the weak convergence in \( \mathcal{J}_{2}(\Omega) \) (176) and (174), we find

\[ \text{curl} \ U_{4} \rightarrow \text{curl} \ U_{4} = 0 \text{ in } L^{2}(\Omega), \quad U_{4}^{n} \rightarrow U_{4}^{\top} = 0 \text{ in } L^{2}(\Gamma_{A}), \quad \text{as } n \rightarrow +\infty. \]

So, \( U_{4} \in \mathcal{H}_{0,\Gamma_{A}}(\text{curl}0;\Omega) \). Together with \( U_{4} \in \mathcal{J}_{2}(\Omega) \), this means that \( U_{4} \) belongs both to \( \mathcal{Z}(\Omega;\Gamma_{A}) = \mathcal{H}_{0,\Gamma_{A}}(\text{curl}0;\Omega) \cap \mathcal{H}_{0,\Gamma_{p}}(\text{div}0;\Omega) \) and to its orthogonal \( \mathcal{H}_{0,\Gamma_{p}}(\text{curl}0;\Omega) \) (cf. (125)), whence \( U_{4} = 0 \).

On the other hand, (171) and (175) imply that

\[ 1 = \lim_{n \rightarrow +\infty} \| U^{n} \|_{X}^{2} = \lim_{n \rightarrow +\infty} \epsilon_{0} c^{2} \| U_{4}^{n} \|^{2} = \epsilon_{0} c^{2} \| U_{4} \|^{2}, \]

in particular, \( U_{4} \neq 0 \), and the above conclusion is contradicted. The proof is complete. \[ \square \]

**Proposition 8.8.** The resolvent of the operator \( -\tilde{\mathcal{A}}_{2} \) satisfies the condition (139) with \( \ell = 2 \).

**Proof.** We follow the lines of the proof of Proposition 8.5, only insisting on the differences. Assume that (139) does not hold, with \( \ell \in \mathbb{N} \) to be specified later, then there exists a sequence \( (\beta_{n})_{n \in \mathbb{N}} \) on \( \mathbb{R} \) with \( |\beta_{n}| \rightarrow \infty \) as \( n \rightarrow +\infty \), and a sequence \( (U^{n})_{n \in \mathbb{N}} = [(U_{1}^{n}, U_{2}^{n}, U_{3}^{n}, U_{4}^{n})^{\top}]_{n} \) on \( D(\tilde{\mathcal{A}}_{2}) \), such that:

\[ \| U^{n} \|_{X} = 1, \quad \forall n, \quad (177) \]

and

\[ \beta_{n}^{\ell} \left( (i\beta_{n}\mathbb{I} + \mathcal{A}_{2}) U^{n} \right) \bigg\|_{X} \rightarrow 0 \quad \text{as } n \rightarrow +\infty; \quad (178) \]

again, the latter condition is equivalent to the system (154)–(157), with different boundary conditions.

Using the monotonicity of \( \mathcal{A}_{2} \) (Equation (53)) and (177):

\[ \beta_{n}^{\ell} \left( \sum_{s} \left( \frac{\nu_{s} U_{s}^{n}}{\omega_{ps}} \right) U_{s}^{n} \right) + \epsilon_{0} c^{3} |\beta_{n}| \| U_{4}^{n} \|_{L^{2}(\Gamma_{A})}^{2} = \beta_{n}^{\ell} \text{Re} \left( (i\beta_{n}\mathbb{I} + \mathcal{A}_{2}) U^{n}, U^{n} \right)_{X} \leq \beta_{n}^{\ell} \left\| (i\beta_{n}\mathbb{I} + \mathcal{A}_{2}) U^{n} \right\|_{X}, \]

we infer from (178) that:

\[ \beta_{n}^{\ell} U_{s}^{n} \rightarrow 0, \quad \text{in } L^{2}(\Omega) \quad \text{as } n \rightarrow +\infty, \quad s = 1, 2, \quad (179) \]

and

\[ \beta_{n}^{\ell} \| U_{4}^{n} \|_{L^{2}(\Gamma_{A})}^{2} \rightarrow 0, \quad \text{as } n \rightarrow +\infty. \quad (180) \]
Furthermore, under the assumptions of Theorem 4.10, conditional exponential stability in the Silver–Müller case holds if
\[ \beta_n^{\frac{\ell}{\ell - 1}} \mathbf{U}_3^n \to 0 \quad \text{in} \quad L^2(\Omega), \quad \text{as} \quad n \to +\infty, \]
\[ \beta_n^{\frac{\ell}{\ell - 2}} \text{curl} \mathbf{U}_4^n \to 0, \quad \text{in} \quad L^2(\Omega) \quad \text{as} \quad n \to +\infty, \] (181) (182)
which yields (162) again. Then, using the Green formula (19) and the Silver–Müller boundary condition, we find:
\[
\beta_n^{\frac{\ell}{\ell - 2}} \left( \text{curl} \mathbf{U}_3^n \mid \mathbf{U}_4^n \right) = \beta_n^{\frac{\ell}{\ell - 2}} \left( \mathbf{U}_3^n \mid \text{curl} \mathbf{U}_4^n \right) - \beta_n^{\frac{\ell}{\ell - 2}} \gamma_\Omega \langle \mathbf{U}_3^n \times \mathbf{n}, \mathbf{U}_4^n \rangle_{\Gamma_\Omega} \\
= \langle \mathbf{U}_3^n \mid \beta_n^{\frac{\ell}{\ell - 2}} \text{curl} \mathbf{U}_4^n \rangle + c \beta_n^{\frac{\ell}{\ell - 2}} \| \mathbf{U}_4^n \|_{L^2(\Gamma_\Omega)}. \] (183)
But, on the other hand, according to (180),
\[ \beta_n^{\frac{\ell}{\ell - 2}} \| \mathbf{U}_4^n \|_{L^2(\Gamma_\Omega)} = \beta_n^{\frac{\ell}{\ell - 2}} \times \left( \beta_n^{\frac{\ell}{\ell - 2}} \| \mathbf{U}_4^n \|_{L^2(\Gamma_\Omega)} \right) \to 0 \quad \text{as} \quad n \to +\infty, \]
for all \( \ell > 0. \) Moreover, Equation (181) implies that the first term on the right-hand side of (183) converges to 0 if \( \ell \geq 2. \) As a consequence,
\[ \beta_n^{\frac{\ell}{\ell - 2}} \left( \text{curl} \mathbf{U}_3^n \mid \mathbf{U}_4^n \right) \to 0, \quad \text{as} \quad n \to +\infty \] (184)
for \( \ell \geq 2, \) which together with (162) implies (167). Again, this implies \( \| \mathbf{U}^n \|_{X} \to 0, \) contradicting the assumption (177). □

The above results allow us to conclude…

**Theorem 8.9.** The semigroup of contractions \((\tilde{T}_2(t))_{t \geq 0}, \) with generator \(-\tilde{A}_2, \) is polynomially stable on \( \tilde{X}_2, \) i.e., there exist a constant \( C > 0 \) such that
\[ \forall t > 1, \quad \| \tilde{T}_2(t) \tilde{U}_0 \|_{\tilde{X}_2} \leq C t^{-\frac{1}{2}} \| \tilde{U}_0 \|_{D(\tilde{A}_2)}, \quad \forall \tilde{U}_0 \in D(\tilde{A}_2). \] (185)
Furthermore, under the assumptions of Theorem 4.10 on \( B_0, \) there exists a constant \( M > 0 \) such that the solution to Problem (50) satisfies
\[ \forall t > 1, \quad \| T_2(t) U_0 - (0, 0, 0, P_2 B_0)^\top \|_{X_2} \leq M t^{-\frac{1}{2}} \| U_0 \|_{D(\tilde{A}_2) \cap X_2}, \quad \forall U_0 \in D(\tilde{A}_2) \cap X_2. \] (186)

**8.3. Conditional exponential stability in the Silver–Müller case**

**Proposition 8.10.** Suppose that the divergence-free, source-free Maxwell system with Silver–Müller, or mixed, boundary condition:
\[
\begin{cases}
\partial_t \mathbf{E} = c^2 \text{curl} \, \mathbf{B}, & \partial_t \mathbf{B} = -\text{curl} \, \mathbf{E}, \quad \text{in} \quad \Omega \times \mathbb{R}_{>0}, \\
\text{div} \, \mathbf{E} = 0, & \text{div} \, \mathbf{B} = 0, \quad \text{in} \quad \Omega \times \mathbb{R}_{>0}, \\
\mathbf{E} \times \mathbf{n} = 0, & \mathbf{B} \cdot \mathbf{n} = 0, \quad \text{on} \quad \Gamma_p \times \mathbb{R}_{>0}, \\
\mathbf{E} \times \mathbf{n} + c \mathbf{B}^\top = 0, & \text{on} \quad \Gamma_\Omega \times \mathbb{R}_{>0}.
\end{cases}
\] (187)
is exponentially stable. Then, the resolvent of the operator \(-\tilde{A}_2, \) satisfies:
\[ \sup_{\beta \in \mathbb{R}} \| (i\beta + \tilde{A}_2)^{-1} \| < \infty. \] (188)
Proof. Again, we use a contradiction argument. Assume there exists a sequence \((\beta_n)\) on \(\mathbb{R}\), with \(|\beta_n| \to +\infty\) as \(n \to +\infty\), and a sequence of fields \((U^n) = (U^n_1, U^n_2, U^n_3, U^n_4)\) on \(D(\tilde{k}_2)\) satisfying (171) and (172), the latter being equivalent to the system (142)–(145). Following the same reasoning as in Proposition 8.7, we get

\[
\|U^n_s\| \to 0, \text{ as } n \to +\infty, \quad s = 1, 2; \tag{189}
\]

\[
\|U^n_4\|_{L^2(\Gamma_A)} \to 0, \text{ as } n \to +\infty. \tag{190}
\]

In order to use the exponential stability of (187), we need to correct \(U^n_3\) since it does not satisfy \(\text{div } U^n_3 = 0\) in \(\Omega\). Let \(\varphi \in H^1_0(\Omega)\) be the unique solution to

\[
(\text{grad } \varphi_n | \text{grad } \psi) = (U^n_3 | \text{grad } \psi), \quad \forall \psi \in H^1_0(\Omega). \tag{191}
\]

Now, define

\[
\hat{U}^n_3 = U^n_3 - \text{grad } \varphi_n, \text{ in } \Omega.
\]

Then, \(\hat{U}^n_3\) belongs to \(H^1_0, \Gamma_P(\text{curl}; \Omega)\) and it satisfies

\[
\text{div } \hat{U}^n_3 = 0 \text{ in } \Omega. \tag{192}
\]

Introduce

\[
L_n := i\beta_n\varepsilon_0 U^n_3 + \sum_s U^n_s - \varepsilon_0 c^2 \text{curl } U^n_4,
\]

the l.h.s. of (144); by assumption \(\|L_n\| \to 0\). By choosing \(\psi = \varphi_n\) in (191) and using the Green formula (18), we find

\[
\|\text{grad } \varphi_n\|^2 = \frac{1}{i\beta_n\varepsilon_0} \int_\Omega (L_n - \sum_s U^n_s + \varepsilon_0 c^2 \text{curl } U^n_4) \cdot \text{grad } \varphi_n \, d\Omega
\]

\[
= \frac{1}{i\beta_n\varepsilon_0} \int_\Omega (L_n - \sum_s U^n_s) \cdot \text{grad } \varphi_n \, d\Omega
\]

\[
\leq \frac{C}{|\beta_n|} (\|L_n\| + \sum_s \|U^n_s\|) \|\text{grad } \varphi_n\|.
\]

Then, by (144) and (189) we deduce that

\[
\|\beta_n \text{grad } \varphi_n\| \to 0, \text{ as } n \to +\infty. \tag{193}
\]

We now introduce

\[
\hat{L}_n = L_n - \sum_s U^n_s - i\beta_n\varepsilon_0 \text{grad } \varphi_n,
\]

\[
Q_n = i\varepsilon_0 c^2 \beta_n U^n_4 + \varepsilon_0 c^2 \text{curl } U^n_3.
\]

By (145), (189) and (193), it holds that:

\[
\hat{L}_n, Q_n \to 0 \in L^2(\Omega), \text{ as } n \to +\infty. \tag{194}
\]

To summarize, the pair \((\hat{U}^n_3, U^n_4)\) satisfies the perfectly conducting boundary condition on \(\Gamma_P\), the Silver–Müller boundary condition on \(\Gamma_A\), and the divergence-free harmonic Maxwell problem in \(\Omega\):

\[
\begin{cases}
 i\beta_n\varepsilon_0 \hat{U}^n_3 - \varepsilon_0 c^2 \text{curl } U^n_4 = \hat{L}_n, \\
 i\varepsilon_0 c^2 \beta_n U^n_4 + \varepsilon_0 c^2 \text{curl } \hat{U}^n_3 = Q_n.
\end{cases} \tag{195}
\]
By assumption, the system (187) is exponentially stable; thus, according to Theorem 8.1, its resolvent is uniformly bounded on the imaginary axis. In other words, there exists a positive constant $C$, independent of $n$, such that the solution $(\hat{U}^n_3, U^n_4)$ to (195) satisfies

$$\|\hat{U}^n_3\| + \|U^n_4\| \leq C \left( \|\hat{L}_n\| + \|Q_n\| \right).$$

From (194), we deduce that

$$\|\hat{U}^n_3\| + \|U^n_4\| \to 0, \quad \text{as } n \to +\infty,$$

and finally by (193) we get

$$\|U^n_3\| + \|U^n_4\| \to 0, \quad \text{as } n \to +\infty,$$

which together with (189) gives the desired contradiction of (140).

Using again Theorem 8.1, we obtain a conditional improved version of the decay Theorem 8.9.

**Theorem 8.11.** Assume that the divergence-free Maxwell system (187) is exponentially stable. Then, the semigroup of contractions $(\hat{T}_2(t))_{t \geq 0}$, with generator $-\hat{A}_2$, is exponentially stable on $\hat{X}_2$, i.e., there exist two constants $C, \gamma > 0$ such that

$$\forall t \geq 0, \quad \|\hat{T}_2(t)\hat{U}_0\|_{\hat{X}_2} \leq C e^{-\gamma t}\|\hat{U}_0\|_{\hat{X}_2}, \quad \forall \hat{U}_0 \in \hat{X}_2. \quad (196)$$

Furthermore, under the assumptions of Theorem 4.10 on $B_0$, there exists a constant $M > 0$ such that the solution to Problem (50) satisfies

$$\forall t \geq 0, \quad \|T_2(t)U_0 - (0, 0, 0, P_2B_0)^\top\|_{X_2} \leq M e^{-\gamma t}\|U_0\|_{X_2}, \quad \forall U_0 \in X_2.$$

**Remark 8.12.** Examples of sufficient conditions for the exponential stability of the Maxwell system with pure Silver–Müller or mixed boundary conditions are given in the seminal papers [15, 22].

**Remark 8.13.** On the other hand, our model with perfectly conducting boundary condition everywhere ($\Gamma_A = \emptyset$) is never exponentially stable: there exists no improved version of Theorem 8.6. In this case, the Maxwell operator has an infinite number of eigenvalues on the imaginary axis: the associated evolution operator cannot be exponentially stable.

Consider the eigenvalue problem with perfectly conducting boundary condition:

$$c^2 \text{curl} \text{curl } E_k = \lambda_k^2 E_k, \quad \text{div } E_k = 0 \quad \text{in } \Omega, \quad E_k \cdot n = 0 \quad \text{on } \Gamma. \quad (197)$$

It is well-known (see, e.g., [3, §8.2.1]) that it admits a nondecreasing sequence of eigenvalues tending to infinity. Assume that the corresponding eigenvectors are normalized by $\|E_k\| = 1$, and introduce the sequence $(U^k)_{k \in \mathbb{N}}$ on $D(\bar{A}_1)$ as:

$$U^k_s = (i\lambda_k I + M_s)^{-1} \varepsilon \omega_p^2 E_k, \quad s = 1, 2, \quad U^k_3 = E_k, \quad U^k_4 = -\frac{1}{i\lambda_k} \text{curl } E_k.$$

Thanks to §6, it is easily shown that $\lambda_k \to +\infty$ implies $(i\lambda_k I + M_s)^{-1} \to 0$. Therefore, $\|U^k_s\| \to 0$ as $k \to +\infty$, and:

$$(i\lambda_k + \bar{A}_1) U^k = \left(0, 0, \frac{1}{c}, (U^k_1 + U^k_2), 0 \right)^\top \to 0 \quad \text{in } L^2(\Omega), \quad \text{as } k \to +\infty.$$

On the other hand, taking $E_k$ as a test function in (197), one finds $\|U^k_s\| = 1/c$. All in all, $0 < U_* \leq \|U^k\| \leq U^* < +\infty$, for some $U_*, U^*$ independent of $k$. This shows that the counterpart of (138) or (188) cannot hold for $-\bar{A}_1$. 
8.4. Convergence to the harmonic regime

A time-harmonic solution to the model (10)–(16) is a particular solution such that \( \mathbf{U}(t, x) = \mathbb{R} \left[ \mathbf{U}(x) e^{-i\omega t} \right] \). Such a solution may only exist if two conditions are satisfied: (i) the forcing or Silver–Müller data is time-harmonic \( (g(t, x) = \mathbb{R} \left[ g(x) e^{-i\omega t} \right]) \) and (ii) the initial data match \( (U_0(x) = \mathbb{R} \left[ U(x) \right]) \). Of course, the general condition (63) must also hold.

The time-harmonic version of (10)–(13), i.e., with \( \partial_t \to -i\omega \), has been studied in [4]. Under Hypothesis 1 and 2, its well-posedness has been established with slightly different boundary conditions, but the adaptation to the Silver–Müller case is not difficult. Indeed, the solution to time-harmonic problem, supplemented with boundary conditions formally similar to (15)–(16), can be expressed with the tools introduced in this paper. The harmonic variables will be denoted with upright bold letters: \( \mathbf{J}, \mathbf{E}, \mathbf{B}, \) etc.

Let \( \mathbf{g} \in \widetilde{\mathbb{T}}(\Gamma_A) + \mathbb{T}C(\Gamma_A) \). As in §4.2.2, set:

\[
(g_3, g_4) \in H_{0, \Gamma_p}(\text{curl}; \Omega) \times H(\text{curl}; \Omega) \quad \text{s.t.} \quad g_3 \times \mathbf{n} + c g_{4\Gamma} = \mathbf{g} \text{ on } \Gamma_A, \quad J_1^* = J_1, \quad J_2^* = J_2, \quad E^* = E - g_3, \quad B^* = B - g_4.
\]

The variable \( \mathbf{U}^* \in D(\mathbb{A}_2) \) is solution to

\[
-i\omega \mathbf{U}^* + \mathbb{A}_2 \mathbf{U}^* = (\varepsilon_0 \omega_p^2 g_3, \varepsilon_0 \omega_p^2 g_3, i\omega g_3 + c^2 \text{curl} g_4, i\omega g_4 - \text{curl} g_3)\top,
\]

a well-posed equation according to Proposition 7.11. Then \( \mathbf{U} := \mathbf{U}^* + (0, 0, g_3, g_4)\top \) is solution to the time-harmonic problem. Obviously, the difference of two solutions belongs to \( D(\mathbb{A}_2) \) and satisfies \( -i\omega \mathbf{U} + \mathbb{A} \mathbf{U} = 0 \), hence it vanishes by Proposition 7.10.

**Definition 8.14.** For any \( \mathbf{g} \in \widetilde{\mathbb{T}}(\Gamma_A) + \mathbb{T}C(\Gamma_A) \), we denote \( H[\mathbf{g}] := \mathbf{U} \), the unique solution to the time-harmonic problem constructed by the above procedure.

By uniqueness, any lifting \( (g_3, g_4) \) of the boundary data \( \mathbf{g} \) can actually be used. For instance, it is possible to take \( g_4 \in H_{0, \Gamma_p; \text{flux}, \Gamma_A, \Sigma}(\text{div}; \Omega) \). Starting with \( (g_3^0, g_4^0) = R_A[\mathbf{g}] \), one defines \( \varphi \in H^1_{0, \Gamma_A}(\Omega) := \{ w \in H^1(\Omega) : w|_{\Gamma_A} = 0 \} \) as the solution to

\[
(\text{grad} \varphi | \text{grad} \psi) = (g_3^0 | \text{grad} \psi), \quad \forall \psi \in H^1_{0, \Gamma_A}(\Omega),
\]

and \( g_4^1 := g_4^0 - \text{grad} \varphi \). By (67), \( g_4^1 \in H_{0, \Gamma_p}(\text{div}; \Omega) \) and \( g_4^1|_{\Gamma_A} = g_4^0|_{\Gamma_A} \) on \( \Gamma_A \). Then one sets:

\[
g_3 = g_3^0, \quad g_4 = g_4^1 - P_2 g_4^1;
\]

recall that \( P_2 \) is the orthogonal projection onto \( Z(\Omega; \Gamma_A) \). By (125), \( g_4 \in H_{0, \Gamma_p; \text{flux}, \Gamma_A, \Sigma}(\text{div}; \Omega) \), and \( g_{4\Gamma} = g_{4\Gamma}^1 = g_{4\Gamma}^0 \) on \( \Gamma_A \), i.e., \( g_3 \times \mathbf{n} + c g_{4\Gamma} = \mathbf{g} \).

**Proposition 8.15.** The range of the mapping \( H \) is included in \( \mathbb{X}_2 \).

**Proof.** Let \( \mathbf{g} \in \widetilde{\mathbb{T}}(\Gamma_A) + \mathbb{T}C(\Gamma_A) \). Take \( g_4 \in H_{0, \Gamma_p; \text{flux}, \Gamma_A, \Sigma}(\text{div}; \Omega) \) as above. As \( g_3 \in H_{0, \Gamma_p}(\text{curl}; \Omega) \) by definition, its curl also belongs to \( H_{0, \Gamma_p; \text{flux}, \Gamma_A, \Sigma}(\text{div}; \Omega) \). Hence, the right-hand side of (198) actually belongs to \( \mathbb{X}_2 \). By Proposition 7.13 the solution also belongs to this space, and so does finally \( \mathbf{U} = \mathbf{U}^* + (0, 0, g_3, g_4)\top \).

By uniqueness of the solution to the time-dependent model (10)–(16), \( U^1(t, x) = \mathbb{R} \left[ H[\mathbf{g}](x) e^{-i\omega t} \right] \) is the solution to the said system, with the Silver–Müller data \( g(t, x) = \mathbb{R} \left[ g(x) e^{-i\omega t} \right] \) and the “well-prepared” initial condition \( U_0^1(x) = \mathbb{R} \left[ H[\mathbf{g}](x) \right] \). Thus, the necessary conditions stated at the beginning of this Subsection are actually sufficient.
On the other hand, if the forcing is still time-harmonic, but the initial condition satisfies (10)–(16) does not have a time-harmonic form. However, if the initial condition satisfies both the compatibility condition and the physical requirements for a magnetic field, then the solution converges to the time-harmonic one as fast as the solution to the homogeneous system converges to 0.

Theorem 8.16. Let \( U = (J_1, J_2, E, B)^\top \) be the solution to (10)–(16) with the time-harmonic Silver–Müller data \( g(t, x) = \Re \left[ g(x) e^{-i\omega t} \right] \), where \( g \in \mathbb{T}(\Gamma_A) + \mathbb{T}(\Gamma_A) \), and the initial data \( U_0 = (J_{1,0}, J_{2,0}, E_0, B_0)^\top \) satisfying (63) and \( B_0 \in H_{0,\Gamma_P:\text{flux},\Gamma_A,\Sigma}(\text{div}; \Omega) \). There exists \( K(g, U_0) \) such that:
\[
\|U(t) - U^\omega(t)\|_X \leq K(g, U_0) \phi(t),
\]
where \( U^\omega(t, x) = \Re \left[ H[g(x) e^{-i\omega t}] \right] \), and the decay function \( \phi(\cdot) \) can be taken in all cases as \( \phi(t) = t^{-\frac{1}{2}} \) for \( t > 1 \), and as \( \phi(t) = e^{-\gamma t} \) if the divergence-free Maxwell system (187) is stable.

Proof. The difference \( U - U^\omega \) is solution to (10)–(16) with homogeneous Silver–Müller boundary condition. Furthermore, the initial data \( U_0 - \Re H[g] \) satisfies the same boundary condition; by construction, it belongs to \( \mathfrak{X}_2 \) by Proposition 8.15; while its third and fourth components belong to \( H_{0,\Gamma_P}(\text{curl}; \Omega) \times H(\text{curl}; \Omega) \). All in all, \( U_0 - \Re H[g] \in D(\mathfrak{A}_2) \): one can apply the estimate (185), and even (196) under the assumptions of Theorem 8.11. □

Acknowledgement. The authors are indebted to Serge Nicaise for useful remarks and discussions.

REFERENCES

[1] C. Amrouche, C. Bernardi, M. Dauge and V. Girault, Vector potentials in three-dimensional non-smooth domains. Math. Meth. Appl. Sci. 21 (1998) 823–864.

[2] W. Arendt and C. J. K. Batty, Tauberian theorems and stability of one-parameter semigroups. Trans. Amer. Math. Soc. 305(2) (1988) 837–852.

[3] F. Assous, P. Ciarlet Jr. and S. Labrunie, Mathematical foundations of computational electromagnetism. Applied Mathematical Sciences vol. 198, Springer, 2018.

[4] A. Back, T. Hattori, S. Labrunie, J.R. Roche and P. Bertrand, Electromagnetic wave propagation and absorption in magnetised plasmas: variational formulations and domain decomposition. ESAIM: M2AN 49 (2015) 1239–1260.

[5] H. Barucq, B. Hanouzet, Asymptotic behavior of solutions to Maxwell’s system in bounded domains with absorbing boundary Silver–Müller’s condition on the exterior boundary, Asymptotic Analysis 15 (1997) 25–40.

[6] A. Borichev, Y. Tomilov, Optimal polynomial decay of functions and operator semigroups, Math. Ann. 347 (2010) 455–478.

[7] A. Buffa and P. Ciarlet Jr., On traces for functional spaces related to Maxwell’s equations. Part I: An integration by parts formula in Lipschitz polyhedra. An integration by parts formula in Lipschitz polyhedra. Math. Meth. Appl. Sci. 24 (2001) 9–30.

[8] A. Buffa and P. Ciarlet Jr., On traces for functional spaces related to Maxwell’s equations. Part II: Hodge decompositions on the boundary of Lipschitz polyhedra and applications, Math. Meth. Appl. Sci. 24 (2001) 31–48.

[9] T. Cazenave and A. Haraux, An Introduction to Semilinear Evolution Equations. Oxford Lecture Series in Mathematics and its Applications 13, Oxford University Press, Oxford, 1998.

[10] P. G. Ciarlet, Introduction à l’analyse numérique matricielle et à l’optimisation, Masson Paris Milan Barcelone Mexico, 1988.

[11] M. Eller, J. Lagnese, S. Nicaise, Decay rates for solutions of a Maxwell system with nonlinear boundary damping, Comput. Appl. Math. 21 (1) (2002) 135–165.

[12] P. Fernandes and G. Gilardi, Magnetostatic and electrostatic problems in inhomogeneous anisotropic media with irregular boundary and mixed boundary conditions. Math. Models Meth. Appl. Sci. 7 (1997) 957–991.

[13] T. Hattori, Décomposition de domaine pour la simulation Full-Wave dans un plasma froid. Thèse, Université de Lorraine (2014). Online: http://docnum.univ-lorraine.fr/public/DOCC_T_2014_0380_HATTORI.pdf.

[14] J. Lagnese, Characteristic conditions for exponential stability of linear dynamical systems in Hilbert spaces. Ann. Differential Equations 1 (1) (1985) 43–56.

[15] V. Komornik, Boundary stabilization, observation and control of Maxwell’s equations. PanAm. Math. J. 4 (1994) 47–61.

[16] S. Labrunie and I. Zaafrani, Dynamique d’un plasma magnétique froid. Prépublication HAL no. 01572067, version 2, 2017. Online: https://hal.archives-ouvertes.fr/hal-01572067v2/document

[17] Y. I. Lyubich and Q. P. Vu, Asymptotic stability of linear differential equations in Banach spaces. Studia Math. 88(1) (1988) 37–42.
[18] S. Nicaise, Stabilization and asymptotic behavior of dispersive medium models. *Systems Control Lett.* **61**(5) (2012), 638–648.
[19] S. Nicaise, Stabilization of a Drude / vacuum model. *Journal of Analysis and its Applications* **37**(3) (2018) 349–375.
[20] S. Nicaise, C. Pignotti, Boundary stabilization of Maxwell’s equations with space-time variable coefficients, *ESAIM Control Optim. Calc. Var.* **9** (2003) 563–578.
[21] A. Pazy, *Semigroups of Linear Operators and Applications to Partial Differential Equations*. Applied Mathematical Sciences vol. **44**, Springer-Verlag, 1983.
[22] K.D. Phung, Contrôle et stabilisation d’ondes électromagnétiques, *ESAIM Control Optim. Calc. Var.* **5** (2000) 87–137.
[23] J. Prüss, On the spectrum of $\mathcal{C}_0$-semigroups. *Trans. Amer. Math. Soc.* **284**(2) (1984) 847–857.
[24] T. H. Stix. *Waves in plasmas*. American Institute of Physics, New York (1992).
[25] J. Viquerat, M. Klemm, S. Lanteri, and C. Scheid, Theoretical and numerical analysis of local dispersion models coupled to a discontinuous Galerkin time-domain method for Maxwell's equations. *Technical Report* 8298, INRIA, 2013. Online: https://hal.inria.fr/hal-00819758v2/document.
[26] C. Weber, A local compactness theorem for Maxwell’s equations. *Math. Meth. Appl. Sci.* **2** 12–25 (1980).