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Hysteresis for ferromagnetism: asymptotics of some 2-scale Landau-Lifshitz model

Eric Dumas∗, Stéphane Labbé†

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Abstract. We study a 2-scale version of the Landau-Lifshitz system of ferromagnetism, introduced by Starynkevitch to modelize hysteresis: the response of the magnetization is fast compared to a slowly varying applied magnetic field. Taking the exchange term into account, in space dimension 3, we prove that, under some natural stability assumption on the equilibria of the system, the strong solutions follow the dynamics of these equilibria. We also give explicit examples of relevant equilibria and exterior magnetic fields, when the ferromagnetic medium occupies some ellipsoidal domain.

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1 Introduction

Hysteresis is a widely studied, yet not completely understood phenomenon. It has played a role from the very beginning of the works on magnetism. Lord Rayleigh [9] proposed a model for ferromagnetic hysteresis in 1887, while the most achieved micromagnetism theory goes back to Landau and Lifshitz, in 1935 (see [7]).

In [12], Visintin gives many historical references, underlines the links between several forms of hysteresis (in particular, from plasticity, and from ferromagnetism), and how it is related to phase transitions. He performs a mathematical study of the so-called hysteresis operators, including the most famous one, due to Preisach.

Recently in [3], Carbou, Efendiev and Fabrie have proved the existence of strong solutions to a model of ferromagnetic hysteresis due to Efendiev.

In this paper, we rather investigate properties of a two-scale model introduced by Starynkevitch in [11]. This model describes the dynamics obtained when some exterior magnetic field is applied to the ferromagnetic material under consideration, while the response of the magnetization occurs on a much shorter time scale (say, denoted by $\varepsilon > 0$). Mathematically, such models, associated to ordinary differential equations, had been studied in the nonstandard analysis framework, leading to “canard cycles” (see [6]). Considering a Landau-Lifshitz model in 0 space dimension (thus, an ODE), Starynkevitch studies the possible equilibria of the system, and the asymptotic behavior of the solutions (as the above mentioned parameter $\varepsilon$ goes to zero) when the exterior magnetic field slowly varies.

Our aim is to extend Starynkevitch’s approach to the Landau-Lifshitz model in space dimension three, taking exchange term into account. This means, giving the asymptotic description of solutions to the slow-fast corresponding system of partial differential equations. Here, we prove such a result away from the bifurcation points of hysteresis loops. More precisely, assuming that the system (described by its magnetization) possesses at each time $t$ some stable equilibrium $m_{eq}(t)$, and is submitted to some slowly varying exterior magnetic field, we show that the magnetization follows the dynamics of $m_{eq}$. We also give explicit examples (for ellipsoidal domains) of relevant equilibria and exterior magnetic fields.
2 Statement of the results

The initial and boundary value problem associated to the 2 scale Landau-Lifshitz equation considered reads:

\[\begin{align*}
\varepsilon \partial_t m^\varepsilon &= m^\varepsilon \wedge h_T^\varepsilon - \alpha m^\varepsilon \wedge (m^\varepsilon \wedge h_T^\varepsilon), \quad \text{for } t \geq 0, x \in \Omega, \\
\partial_n m^\varepsilon_{\mid_{t=0}} &= 0, \\
m^\varepsilon_{\mid_{t=0}} &= m_0.
\end{align*}\]  

(2.1)

The unknown is the magnetization \(m^\varepsilon\), function of the time variable \(t \geq 0\) and of the space variable \(x \in \Omega\), with values in the sphere \(S^2 \subset \mathbb{R}^3\). The domain \(\Omega\) occupied by the ferromagnet is a subset of \(\mathbb{R}^3\). Furthermore, \(h_T^\varepsilon = h_T(t, m^\varepsilon(t))\), where the total magnetic field \(h_T\) is defined by

\[h_T(t, m) = \Delta m + h_d(m) + h_{\text{ext}}(t).\]  

(2.2)

Here, the first term \(\Delta m\) is the “exchange term”, which tends to impose a constant magnetization (domains where magnetization is constant are called “Weiss domains”), and \(\Delta m\) denotes the extension of \(\Delta m\) by 0 out of \(\Omega\). The second term, yielding spatial variations of the magnetization, is the “demagnetizing field” \(h_d(m)\), which results from a quasi-stationary approximation of Maxwell’s equations; it is defined (at least, for \(m \in L^2(\Omega, \mathbb{R}^3)\), as an element of \(L^2(\mathbb{R}^3, \mathbb{R}^3)\)) by

\[\text{curl } h_d(m) = 0 \quad \text{and} \quad \text{div } (h_d(m) + m) = 0 \quad \text{in } \mathbb{R}^3.\]

Classical properties of the mapping \(m \mapsto h_d(m)\) are recalled in Section 3.1. The third term, \(h_{\text{ext}}\), denotes some given exterior field, which is assumed to depend on time (and possibly on space). The positive constant \(\alpha\) is some damping coefficient, which appears in the model when passing from a microscopic to a macroscopic description. The small parameter \(\varepsilon > 0\) expresses the fact that, while the exterior field \(h_{\text{ext}}\) depends on \(t\), and has time variations at scale 1, the magnetization \(m^\varepsilon\) essentially depends on \(t/\varepsilon\), and thus has variations at the much more rapid scale \(\varepsilon\).

Throughout this paper, for any \(s \in \mathbb{N}\), we denote by \(H^s(\Omega)\) the usual Sobolev space of functions with values in some vector space \(\mathbb{R}^N\), whereas \(H^s(\Omega, S^2)\) is the Sobolev space of functions with values in the sphere \(S^2\) (which is not a vector space),

\[H^s(\Omega, S^2) = \{m \in H^s(\Omega) \mid |m| = 1 \text{ almost everywhere} \}.\]

Finally, for \(s \geq 2\), \(H^s_N(\Omega)\) denotes the subspace of functions in \(H^s(\Omega)\) with homogeneous von Neumann boundary condition,

\[H^s_N(\Omega) = \{m \in H^s(\Omega) \mid \partial_n m_{\mid_{\partial\Omega}} = 0\},\]

and

\[H^s_N(\Omega, S^2) = H^s(\Omega, S^2) \cap H^s_N(\Omega).\]

All these spaces (even if not vector spaces) inherit the (metric) topology given by the usual norm on \(H^s(\Omega)\).

We prove the following
Theorem 2.1. Let \( \Omega \) be an open and bounded subset of \( \mathbb{R}^3 \), with smooth boundary. Let \( T > 0 \), and \( h_{\text{ext}} \in C^1([0,T], C^\infty(\mathbb{R}^3)) \), bounded with bounded derivatives. Assume that there exist \( m_{\text{eq}} \in C^1([0,T], H^2_{\text{loc}}(\Omega, S^2)) \) and \( m_0 \in H^2_{\text{loc}}(\Omega, S^2) \) such that

(i) for all \( t_0 \in [0,T] \), \( m_{\text{eq}}(t_0) \) is an equilibrium for

\[
\partial_t m = m \land h_T(t_0, m) - \alpha m \land \left( m \land h_T(t_0, m) \right)
\]

(see (3.1));

(ii) the solution \( m_0 \) to the initial and boundary value problem

\[
\begin{align*}
\partial_t n_0 &= n_0 \land h_T(0, n_0) - \alpha n_0 \land \left( n_0 \land h_T(0, n_0) \right), \\
\partial_n n_0|_{\partial \Omega} &= 0, \\
\left. n_0 \right|_{t=0} &= m_0,
\end{align*}
\]

is global \( (n_0 \in C([0,\infty), H^2_{\text{loc}}(\Omega, S^2))) \), with \( \nabla \Delta n_0 \in L^2((0,\infty) \times \Omega) \), and \( n_0(t) \) converges in \( H^2(\Omega) \), as \( t \to \infty \), towards \( m_{\text{eq}}(0) \);

(iii) the linearized operator \( \mathcal{L}(m_{\text{eq}}) \) given by (4.31) has the following dissipation property:

\[
\begin{align*}
\text{there exist } C_{\text{lin}} > 0 \text{ and } \eta > 0 \text{ such that}, \\
\text{for all } \delta \in C([0,T], H^\infty(\Omega)) \text{ with } |m_{\text{eq}} + \delta| \equiv 1 \text{ and } \partial_n \delta|_{\partial \Omega} = \partial_n \Delta \delta|_{\partial \Omega} = 0, \\
\sup_{t \in [0,T]} \| \delta(t) \|_{H^2(\Omega)} &\leq \eta \text{ implies:} \\
\forall t \in [0,T], \quad \left( \mathcal{L}(t, m_{\text{eq}}(t)) \delta(t) \mid \delta(t) \right)_{H^2(\Omega)} &\leq -C_{\text{lin}} \| \delta(t) \|^2_{H^2(\Omega)}.
\end{align*}
\]

Then, there is \( \varepsilon_0 > 0 \) such that, for all \( \varepsilon \in (0, \varepsilon_0) \), the solution \( m^\varepsilon \) to (2.1) exists up to time \( T \) \( (m^\varepsilon \in C([0,T], H^2_{\text{loc}}(\Omega, S^2))) \), and converges in \( L^2((0,T), H^2(\Omega)) \cap C([t,T], H^2(\Omega)) \) towards \( m_{\text{eq}} \) as \( \varepsilon \to 0 \), for all \( t \in (0,T) \).

To prove Theorem 2.1, we first show that \( m^\varepsilon \) converges to \( m_{\text{eq}}(0) \) within an initial layer of size \( t_\varepsilon = C\varepsilon \ln(1/\varepsilon) \). This is achieved via classical energy estimates (in \( H^2 \)), carefully controlling the dependence upon \( \varepsilon \) — more technically speaking, the quasilinear and elliptic degenerate system of PDE’s in (2.1) is first converted into a perturbation of some linear, strongly elliptic system, yielding the usual smoothing properties, and a Galerkin approximation is used. In a second step, we prove that \( m^\varepsilon \) converges towards \( m_{\text{eq}} \) on the whole time interval \([t_\varepsilon, T]\). This amount to proving of long-time existence and return to equilibrium result for small initial data. Toward this end, we use again energy estimates, together with the stability assumption (2.5).

Figure 1 illustrates this corresponding asymptotic behaviour.

The above assumptions on the equilibrium \( m_{\text{eq}} \) are discussed in Section 3.2 below. In particular, Assumption (ii) in Theorem 2.1 may be understood as a choice of ‘prepared’ data \( m_0 \) allowing to deal with the initial layer \((0, \varepsilon \ln(1/\varepsilon))\).
The dissipation property (2.5) expresses, for all $t_0 \in [0, T]$, the stability of the linearization around $m_{eq}(t_0)$ of (2.1), with $\varepsilon = 1$ and with $h_{ext}$ replaced with $h_{ext}(t_0)$, independent of time. This is a strong assumption, which ensures global existence of the solutions to the corresponding Landau-Lifshitz equation, for initial data close to $m_{eq}(t_0)$:

**Proposition 2.2.** Let $\Omega$ be an open and bounded subset of $\mathbb{R}^3$, with smooth boundary. Consider an exterior magnetic field $h_{ext} \in C^\infty(\mathbb{R}^3)$ (independent of time) bounded with bounded derivatives. Assume that there exists $m_{eq} \in H^2_N(\Omega, S^2)$ (independent of time) satisfying the equilibrium condition

$$m_{eq} \wedge (\Delta m_{eq} + h_d(m_{eq}) + h_{ext}) = 0 \quad \text{on} \ \Omega,$$

as well as the stability condition

there exist $C_{lin} > 0$ and $\eta > 0$ such that,

for all $\delta \in H^\infty(\Omega)$ with $|m_{eq} + \delta| \equiv 1$ and $\partial_\nu \delta |_{\partial \Omega} = \partial_\nu \Delta \delta |_{\partial \Omega} = 0$,\n
$$\|\delta(t)\|_{H^2(\Omega)} \leq \eta \implies \left( L(0, m_{eq})\delta \mid \delta \right)_{H^2(\Omega)} \leq -C_{lin}\|\delta\|_{H^2(\Omega)}^2,$$
for the linearized operator $L(0,m_{\text{eq}})$ given by (4.31) (with $m_{\text{eq}}(0)$ and $h_{\text{ext}}(0)$ replaced with $m_{\text{eq}}$ and $h_{\text{ext}}$, respectively).

Then, there exists $\eta_0 > 0$ such that, for all $m_0 \in H^2_N(\Omega, S^2)$ satisfying

$$\|m_0 - m_{\text{eq}}\|_{H^2(\Omega)} \leq \eta_0,$$

the solution $n$ to the initial and boundary value problem

\[
\begin{aligned}
\partial_t n &= n \wedge h_T(0, n) - \alpha n \wedge (n \wedge h_T(0, n)), \\
\partial_\nu n|_{\partial \Omega} &= 0, \\
n(t=0) &= m_0,
\end{aligned}
\]

is global ($n \in C([0, \infty), H^2_N(\Omega, S^2))$, with $\nabla \Delta (n - m_{\text{eq}}) \in L^2((0, \infty) \times \Omega)$, and $n(t)$ converges in $H^2(\Omega)$, as $t$ goes to $\infty$, towards $m_{\text{eq}}$).

In the case of $m_{\text{eq}}(0)$ constant over $\Omega$, Proposition 2.2 expresses that in Theorem 2.1, assumptions (i) and (iii) imply assumption (ii), so that we get:

**Corollary 2.3.** Let $\Omega$ be an open and bounded subset of $\mathbb{R}^3$, with smooth boundary. Let $T > 0$, and $h_{\text{ext}} \in C^1([0, T], C^\infty(\mathbb{R}^3))$, bounded with bounded derivatives. Assume that there exist $m_{\text{eq}} \in C^1([0, T], H^2_N(\Omega, S^2))$ satisfying assumptions (i) and (iii) from Theorem 2.1. Assume furthermore that $m_{\text{eq}}(0)$ is constant over $\Omega$.

Then, there exist $\eta_0, \varepsilon_0 > 0$ such that, for all $m_0 \in H^2_N(\Omega, S^2)$ such that

$$\|m_0 - m_{\text{eq}}(0)\|_{H^2(\Omega)} \leq \eta_0,$$

and for all $\varepsilon \in (0, \varepsilon_0)$, the solution $m^\varepsilon$ to (2.1) exists up to time $T$ ($m^\varepsilon \in C([0, T], H^2_N(\Omega, S^2))$), and converges in $L^2((0, T), H^2(\Omega)) \cap C([t, T], H^2(\Omega))$ towards $m_{\text{eq}}$ as $\varepsilon$ goes to zero, for all $t \in (0, T)$.

In Lemma 3.5 below, we give examples (in ellipsoidal domains) of equilibria $m_{\text{eq}}$ satisfying the assumptions of Corollary 2.3.

### 3 Preliminaries

#### 3.1 Some functional analysis

In this section, we recall some functional analysis results useful in the sequel. The first of them deals with the continuity properties of the demagnetizing field operator $h_d$, immediately deduced from the Fourier representation \( \hat{h}_d(u)(\xi) = - (\xi \cdot \hat{u}(\xi)) \frac{\xi}{|\xi|^2} \):

**Lemma 3.1** ($h_d$ properties). Let $\Omega$ be an open subset of $\mathbb{R}^3$. For all $s \in \mathbb{N}$ and $u \in H^s(\Omega)$, one has

$$\|h_d(u)\|_{H^s(\mathbb{R}^3)} \leq \|u\|_{H^s(\Omega)}.$$
Furthermore, for all $v \in L^2(\Omega)$ we have
\[ (h_d(u) \mid v)_{L^2(\Omega)} = -(u \mid h_d(v))_{L^2(\Omega)}. \]

In addition to the usual Sobolev embeddings, we recall the following estimate, which results from the coercivity of the operator $A = 1 - \Delta$, with domain $D(A) = \{ m \in H^2(\Omega) \mid \partial_\nu m|_{\partial \Omega} = 0 \}$ (see for example [5])

**Lemma 3.2.** Let $\Omega$ be a smooth bounded open set in $\mathbb{R}^3$. There exists a constant $C > 0$ such that for all $u \in H^2(\Omega)$ one has
\[ \|u\|_{L^\infty(\Omega)} \leq C \left( \|u\|^2_{L^2(\Omega)} + \|\Delta u\|^2_{L^2(\Omega)} \right)^{1/2}. \]

In the sequel, we will need the following definition.

**Definition 3.3.** Let $\Omega$ be a smooth bounded open set in $\mathbb{R}^3$. For $k \in \mathbb{N}^*$, let $P_k$ be the $L^2(\Omega)$-orthogonal projection onto $V_k$, the vector space spanned by the first $k$ eigenfunctions of $A = 1 - \Delta$, with domain $D(A) = \{ m \in H^2(\Omega) \mid \partial_\nu m|_{\partial \Omega} = 0 \}$.

The family of operators $(P_k)_{k \in \mathbb{N}}$ satisfies useful properties:

**Lemma 3.4.** The following properties are true.

(i) $\forall k \in \mathbb{N}^*, \forall u \in D(A)$, $\Delta P_k u = P_k \Delta u$,

(ii) $\forall k \in \mathbb{N}^*, \forall s \in \mathbb{N}$, $\forall u \in H^s(\Omega)$, $P_k u \in H^s(\Omega)$

(and $P_k u \in H^s_N(\Omega)$ when $s \geq 2$),

(iii) $\forall s \in \mathbb{N}$, $\lim_{k \to \infty} \|(1 - P_k)u\|_{H^s(\Omega)} = 0$ for all $u \in H^s(\Omega)$ when $s = 0, 1$, and for all $u \in H^s_N(\Omega)$ when $s \geq 2$.

**Proof.** (i) For all $u$ in $D(A)$, $k$ in $\mathbb{N}^*$, one has
\[ P_k \Delta u = \sum_{j=1}^k (\Delta u \mid \psi_j)_{L^2} \psi_j, \]

with $(\psi_i)_{i \in \mathbb{N}}$ the $L^2$-orthonormal basis of the eigenvectors of $\Delta$ associated to the eigenvalues $(\lambda_i)_{i \in \mathbb{N}}$. Then, using the vanishing Neumann boundary conditions,
\[ (\Delta u \mid \psi_j)_{L^2} = -\int_\Omega \nabla u \cdot \nabla \psi_j = (u \mid \Delta \psi_j)_{L^2}, \]

so that
\[ P_k \Delta u = \sum_{j=1}^k \lambda_j (u \mid \psi_j)_{L^2} \psi_j = \Delta P_k u. \]

Point (ii) follows from the regularity properties of the family $(\psi_i)_{i \in \mathbb{N}}$.

Point (iii) is a consequence of the fact that $u \mapsto \left( \sum_{j=1}^\infty (1 + \lambda_j^s)(u \mid \psi_j)_{L^1}^2 \right)^{1/2}$ provides a norm equivalent to the usual one on $H^s(\Omega)$. \(\square\)
3.2 About equilibria

Global solutions and equilibria. In [1, Th. 4.3], in the case of ellipsoidal domains \(\Omega \subset \mathbb{R}^3\) and under a smallness assumption (on \(\|h_{\text{ext}}\|_{L^\infty}\) and \(\|\Delta m_0\|_{L^2}\)), Alouges and Beauchard construct global smooth solutions to (2.1). Furthermore, these solutions satisfy

\[
\forall T > 0, \quad \|\Delta m(T)\|_{L^2(\Omega)}^2 + C\int_0^T \|\nabla \Delta m\|_{L^2(\Omega)}^2 \leq \|\Delta m_0\|_{L^2(\Omega)},
\]

so that \(\nabla \Delta m\) belongs to \(L^2((0, \infty) \times \Omega)\). This is a part of our assumptions on the equilibrium \(m_{\text{eq}}\), when requiring the existence of the global solution \(n_0\).

Saying that \(m_{\text{eq}}(t_0)\) is an equilibrium for (2.3) means

\[
\begin{cases}
  m_{\text{eq}}(t_0) \wedge h_T(t_0, m_{\text{eq}}(t_0)) = 0, \\
  \partial_v m_{\text{eq}}(t_0)|_{\partial \Omega} = 0,
\end{cases}
\]

and requiring \(H^2\) convergence of \(n_0(t)\) towards \(m_{\text{eq}}(0)\) as \(t\) goes to \(\infty\) implies that \(m_{\text{eq}}(0)\) is an equilibrium for (2.3) with \(t_0 = 0\).

Energy minimization. It is worth noting that energy decay occurs along the evolution of \(n_0(t)\), so that one may hope at least \(H^1\) convergence of \(n_0(t)\) towards some local minimum of the energy, as \(t\) goes to \(\infty\). To the Landau-Lifshitz system (2.1) is associated the energy

\[
\mathcal{E}(t, m) = \frac{1}{2} \int_{\Omega} |\nabla m|^2 - \frac{1}{2} \int_{\Omega} m \cdot h_{\text{d}}(m) - \int_{\Omega} m \cdot h_{\text{ext}}(t),
\]

and when \(m\) is solution to (2.1), we have

\[
\frac{d}{dt} \mathcal{E}(t, m(t)) = -\frac{\alpha}{\varepsilon} \|m(t) \wedge h_T(t, m(t))\|_{L^2(\Omega)}^2 - \int_{\Omega} m(t) \cdot \partial_v h_{\text{ext}}(t).
\]

Since the exterior magnetic field does not depend on time during the evolution of \(n_0\), we get

\[
\frac{d}{dt} \mathcal{E}(t, n_0(t)) = -\alpha \|m_0(t) \wedge h_T(t, n_0(t))\|_{L^2(\Omega)}^2.
\]

In the case of ellipsoidal domains, special configurations are available. See [8], and references therein: there exists a real \(3 \times 3\) definite positive diagonalizable matrix \(D\) giving the demagnetizing field resulting from any magnetization constant constant over \(\Omega\):

\[
\forall v \in \mathbb{R}^3, \quad h_{\text{d}}(v)|_{\Omega} \equiv -Dv.
\]

Hence, if \(u \in S^2\) is an eigenvector of \(D\) associated to the eigenvalue \(d > 0\), and if the exterior magnetic field is \(h_{\text{ext}} = \lambda u\) for some \(\lambda > 0\) (or \(h_{\text{ext}}(x) = \lambda \chi(x)u\))
for some $\chi \in C_c^\infty(\mathbb{R}^3, [0, 1])$ to get a spatially localized field), then the system possesses two explicit equilibria $m_{\text{eq}}^\pm$:

$$m_{\text{eq}}^\pm = \pm u.$$  

One easily computes the energy associated to perturbations of these equilibria: for all $\delta \in H_\text{loc}^2(\Omega, \mathbb{R}^3)$ such that $|m_{\text{eq}}^\pm + \delta| = 1$ a.e.,

$$\mathcal{E}(m_{\text{eq}}^\pm + \delta) - \mathcal{E}(m_{\text{eq}}^\pm) = \frac{1}{2} \int_\Omega |
abla \delta|^2 - \frac{1}{2} \int_\Omega \delta \cdot h_d(\delta) + \frac{1}{2} (\pm \lambda - d) \int_\Omega |\delta|^2.$$

The first two terms are non-negative, so that for $\lambda$ large enough ($\lambda > d$), $m_{\text{eq}}^+$ is a global minimum of $\mathcal{E}$; but for $\lambda$ small, it may fail to be even a local minimum. Concerning $m_{\text{eq}}^-$, for all $\lambda > 0$, if $d$ is the largest eigenvalue of $D$, and $\delta$ is constant in space, then the difference of energies above is less than $-\frac{\lambda}{2} \int_\Omega |\delta|^2$, thus negative, whereas for $\delta$ with large variations, the gradient term dominates, and the energy difference becomes positive. Hence, $m_{\text{eq}}^-$ is always a saddle point for $\mathcal{E}$.

**The dissipation property (2.5).** We have the following lemma, the proof of which is postponed to Section 6.1:

**Lemma 3.5.** For $\lambda > 0$ large enough, the equilibrium $m_{\text{eq}}^+$ from (3.2) satisfies the dissipation property (2.5) (for some constant $C_{\text{lin}}$ depending on $\lambda$).

For $m_{\text{eq}}^-$, it is shown in Section 6.1 that for $\lambda$ large, we have on the contrary:

**Lemma 3.6.** For $\lambda > 0$ large enough, there exist $C = C(\alpha, \lambda) > 0$ and $\eta = \eta(\alpha, \lambda) > 0$ such that, for all $\delta \in C([0, T], H^\infty(\Omega))$ with $|m_{\text{eq}}^- + \delta| \equiv 1$ and $\partial_\nu \delta|_{\partial \Omega} = \partial_\nu \Delta \delta|_{\partial \Omega} = 0$, when $\|\delta\|_{H^2(\Omega)} \leq \eta$, we have:

$$\forall t \in [0, T], \quad \left( \mathcal{L}(t, m_{\text{eq}}^-(t))\delta(t) \right)_{H^2(\Omega)} \geq C\|\delta\|^2_{H^2(\Omega)}.$$

### 4 Proof of Theorem 2.1

First, consider the solution $n_0$ to the Cauchy problem

$$\begin{cases}
\partial_t n_0 = n_0 \wedge h_T(0, n_0) - \alpha n_0 \wedge \left( n_0 \wedge h_T(0, n_0) \right), \\
\partial_\nu n_0|_{\partial \Omega} = 0, \\
n_0|_{t=0} = m_0,
\end{cases}$$

and define $n^\varepsilon$ by

$$\forall t \geq 0, \quad n^\varepsilon(t) = n_0(t/\varepsilon).$$

Then, $n^\varepsilon \in C_b([0, \infty), H^2(\Omega))$ (with $\nabla \Delta n^\varepsilon \in L^2((0, \infty) \times \Omega)$, and we know that

$$t_{\varepsilon}/\varepsilon \xrightarrow{\varepsilon \to 0} \infty \quad \Rightarrow \quad n^\varepsilon(t_{\varepsilon}) \xrightarrow{\varepsilon \to 0} m_{\text{eq}}(0) \text{ in } H^2(\Omega).$$
Next, as in [4], we observe that for smooth functions \( m \) with constant modulus (w.r.t. \( x \)), one has \( m \cdot \Delta m = -2|\nabla m|^2 \), so that smooth solutions to (2.1) equivalently satisfy

\[
\begin{aligned}
\varepsilon \partial_t m^\varepsilon - \alpha \Delta m^\varepsilon &= F(t, m^\varepsilon), \\
\partial_x m^\varepsilon||_{\partial \Omega} &= 0, \\
m^\varepsilon|_{t=0} &= m_0,
\end{aligned}
\]

(4.2)

where

\[
F(t, m) = m \wedge h_T(t, m) + \alpha|\nabla m|^2 m - \alpha m \wedge \left( m \wedge (h_0(m) + h_{ext}(t)) \right).
\]

Furthermore, smooth \( (L^\infty_\varepsilon H^2) \) solutions to (4.2) issued from \( m_0 \) with constant modulus, equal to one, are shown to keep the same modulus for all time, (due to uniqueness of the solution \( a = |m|^2 \) to \( \mathring{\varepsilon} \partial_t a = \alpha \Delta a + 2\alpha|\nabla u|^2(a-1), \partial_x a|_{\partial \Omega} = 0, a|_{t=0} = 1 \)). We thus solve (4.2) in the Banach space \( C([0,T], H^2_N(\Omega)) \), and deduce from this conservation that the solution actually belongs to the space \( C([0,T], H^2_N(\Omega, S^2)) \).

It is worth noting that (2.1) is an initial and boundary value problem for some quasilinear and parabolic degenerate operator, which is seen in (4.2) as a perturbation of a linear and strongly parabolic one.

Standard energy estimates ensure local-in-time existence and uniqueness of solutions continuous in time, with values in \( H^2(\Omega) \) (with an existence time depending on \( \varepsilon \)); see for example [1] or [4]. By the usual continuation argument, we simply need to bound the \( H^2 \) norm of \( m^\varepsilon \) to ensure existence up to time \( T \). Actually, we shall prove convergence (as \( \varepsilon \) goes to zero) at the same time, via energy estimates.

We first show that, after some time \( t_\varepsilon \) of the form \( t_\varepsilon = C\varepsilon \ln(1/\varepsilon) \), \( m^\varepsilon \) and \( n^\varepsilon \) are close: \( \sup_{[0,t_\varepsilon]} ||m^\varepsilon - n^\varepsilon||_{H^2(\Omega)} \) goes to zero with \( \varepsilon \); thus, for \( \varepsilon \) small enough, \( m^\varepsilon(t_\varepsilon) \) is as close (in \( H^2(\Omega) \)) to \( m_{eq}(0) \) as desired. We then use the stability property of \( m_{eq}(t) \) to show that \( m^\varepsilon(t) \) stays close to it, for \( t \in [t_\varepsilon, T] \).

### 4.1 First step: the initial layer \([0, t_\varepsilon]\)

#### 4.1.1 Galerkin scheme

For \( k \in \mathbb{N}^* \), let \( P_k \) be the \( L^2(\Omega) \)-orthogonal projection onto \( V_k \), the vector space spanned by the first \( k \) eigenfunctions of \( A = 1 - \Delta \), with domain \( D(A) = \{ m \in H^2(\Omega) \mid \partial_x m|_{\partial \Omega} = 0 \} \), as in Definition 3.3. Define a Galerkin approximation of (4.2) by:

\[
\begin{aligned}
\varepsilon \partial_t m^\varepsilon_k - \alpha \Delta m^\varepsilon_k &= P_k F(t, m^\varepsilon_k), \\
m^\varepsilon_k|_{t=0} &= P_k m_0.
\end{aligned}
\]

(4.4)

The projection \( n^\varepsilon_k = P_k n^\varepsilon \) also satisfies

\[
\begin{aligned}
\varepsilon \partial_t n^\varepsilon_k - \alpha \Delta n^\varepsilon_k &= P_k F(0, n^\varepsilon_k) + \alpha[P_k, \Delta]n^\varepsilon + P_k \left( F(0, n^\varepsilon) - F(0, n^\varepsilon_k) \right) \\
&= P_k F(0, n^\varepsilon_k) + P_k[P_k, F(0, \cdot)](n^\varepsilon),
\end{aligned}
\]

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since for \( u \in D(A) \), \( P_k \Delta u = \Delta P_k u \), according to Lemma 3.4.

Now, perform energy estimates (in \( L^2 \)) for \( \varphi_k^\varepsilon = m_k^\varepsilon - n_k^\varepsilon \), solution to

\[
\varepsilon \partial_t \varphi_k^\varepsilon - \alpha \Delta \varphi_k^\varepsilon = P_k \left( \mathcal{F}(t, m_k^\varepsilon) - \mathcal{F}(0, n_k^\varepsilon) \right) - P_k [P_k, \mathcal{F}(0, \cdot)](n^\varepsilon), \quad \varphi_k^\varepsilon|_{t=0} = 0.
\]

### 4.1.2 \( L^2 \) estimates

Take the scalar product (in \( L^2(\Omega) \)) of \( \varphi_k^\varepsilon \) with the first equation in (4.5) to get

\[
\frac{\varepsilon}{2} \frac{d}{dt} \left( \| \varphi_k^\varepsilon \|_{L^2(\Omega)}^2 \right) + \alpha \| \nabla \varphi_k^\varepsilon \|_{L^2(\Omega)}^2 = I_1 + I_2 + I_3 + I_4,
\]

with

- \( I_1 = \left( \varphi_k^\varepsilon \cdot m_k^\varepsilon \wedge h_T(t, m_k^\varepsilon) - n_k^\varepsilon \wedge h_T(0, n_k^\varepsilon) \right)_{L^2(\Omega)} \),
- \( I_2 = \alpha \left( \| \nabla m_k^\varepsilon \|^2 m_k^\varepsilon - \| \nabla n_k^\varepsilon \|^2 n_k^\varepsilon \right)_{L^2(\Omega)} \),
- \( I_3 = -\alpha \left( \varphi_k^\varepsilon \cdot m_k^\varepsilon \wedge \left( m_k^\varepsilon \wedge (h_d(m_k^\varepsilon) + h_{ext}(t)) \right) - n_k^\varepsilon \wedge \left( n_k^\varepsilon \wedge (h_d(n_k^\varepsilon) + h_{ext}(0)) \right) \right)_{L^2(\Omega)} \),
- \( I_4 = \left( \varphi_k^\varepsilon \cdot [P_k, \mathcal{F}(0, \cdot)](n^\varepsilon) \right)_{L^2(\Omega)} \).

#### Estimating \( I_1 \).

Decompose \( m_k^\varepsilon = n_k^\varepsilon + \varphi_k^\varepsilon \). For all \( \varphi, h \in \mathbb{R}^3 \), \( \varphi \cdot (\varphi \wedge h) = 0 \), so that

\[
I_1 = \left( \varphi_k^\varepsilon \cdot n_k^\varepsilon \wedge \left( \Delta(n_k^\varepsilon + \varphi_k^\varepsilon) + h_d(n_k^\varepsilon + \varphi_k^\varepsilon) + h_{ext}(t) \right) - n_k^\varepsilon \wedge \left( \Delta(n_k^\varepsilon + h_d(n_k^\varepsilon) + h_{ext}(0)) \right) \right)_{L^2(\Omega)}
= \left( \varphi_k^\varepsilon \cdot n_k^\varepsilon \wedge (\Delta \varphi_k^\varepsilon + h_d(\varphi_k^\varepsilon)) \right)_{L^2(\Omega)} + \left( \varphi_k^\varepsilon \cdot n_k^\varepsilon \wedge (h_{ext}(t) - h_{ext}(0)) \right)_{L^2(\Omega)}.
\]

Using the continuity of \( h_d \) on \( L^2(\Omega) \), we get, for some constant \( C \) depending on \( \| \partial_t h_{ext} \|_{L^\infty} \) and \( \| n_0 \|_{H^\infty((0, \infty), L^2(\Omega))} \):

\[
I_1 \leq C \| \varphi_k^\varepsilon \|_{L^2(\Omega)} \left( \| \varphi_k^\varepsilon \|_{H^2(\Omega)} + t \right).
\]

#### Estimating \( I_2 \).

Write

\[
\| \nabla m_k^\varepsilon \|^2 m_k^\varepsilon - \| \nabla n_k^\varepsilon \|^2 n_k^\varepsilon = (\| \nabla m_k^\varepsilon \|^2 + \| \nabla n_k^\varepsilon \|^2 - \| \nabla n_k^\varepsilon \|^2) m_k^\varepsilon + \| \nabla n_k^\varepsilon \|^2 \varphi_k^\varepsilon
= (\nabla (2n_k^\varepsilon + \varphi_k^\varepsilon) \cdot \nabla \varphi_k^\varepsilon)(n_k^\varepsilon + \varphi_k^\varepsilon) + \| \nabla n_k^\varepsilon \|^2 \varphi_k^\varepsilon.
\]

Then, use Sobolev’s embeddings, such as

\[
\left( \varphi_k^\varepsilon \cdot (\nabla n_k^\varepsilon \cdot \nabla \varphi_k^\varepsilon) n_k^\varepsilon \right)_{L^2(\Omega)} \leq \| \varphi_k^\varepsilon \|_{L^\infty(\Omega)} \| \nabla n_k^\varepsilon \|_{L^2(\Omega)} \| \nabla \varphi_k^\varepsilon \|_{L^4(\Omega)} \| n_k^\varepsilon \|_{L^4(\Omega)}
\leq \| \varphi_k^\varepsilon \|_{H^2(\Omega)} \| n_k^\varepsilon \|_{H^1(\Omega)} \| \nabla \varphi_k^\varepsilon \|_{H^1(\Omega)} \| n_k^\varepsilon \|_{H^1(\Omega)},
\]
Lemma 4.1. For all $I \in (0, \infty)$, there exists a constant $C$ depending on the quantities $\|n_0\|_{L^\infty((0,\infty), H^1(\Omega))}$, to get the estimate

$$I_2 \leq C \|\varphi_k^e\|_{H^2(\Omega)} \left( \|\varphi_k^e\|_{H^2(\Omega)} + \|\varphi_k^e\|_{H^2(\Omega)}^2 \right),$$

for some constant $C$ depending on $\|n_0\|_{L^\infty((0,\infty), H^1(\Omega))}$.

**Estimating $I_3$.** As for $I_1$, cancellations allow to write

$$I_3 = -\alpha \left( \varphi_k^e | n_k \land (n_k \land h_d(\varphi_k^e)) + \varphi_k^e \land h_d(n_k) \right) \bigg|_{L^2(\Omega)}$$

$$- \alpha \left( \varphi_k^e | n_k \land \left( n_k \land (h_{ext}(t) - h_{ext}(0)) \right) \right) \bigg|_{L^2(\Omega)}.$$

Boundedness of $h_d$ on $L^p$ for finite $p$ provides the bounds

$$\|n_k \land (n_k \land h_d(\varphi_k^e))\|_{L^2(\Omega)} \leq \|n_k\|_{L^6(\Omega)}^2 \|\varphi_k^e\|_{L^6(\Omega)},$$

and

$$\|n_k \land \varphi_k^e \land h_d(n_k)\|_{L^2(\Omega)} \leq \|n_k\|_{L^6(\Omega)}^2 \|\varphi_k^e\|_{L^6(\Omega)}.$$ 

The above $L^6$ norms are controlled by $H^1$ norms. Thus, for some constant $C$ depending on $\|h_{ext}\|_{L^\infty}, \|\partial_t h_{ext}\|_{L^\infty}$ and $\|n_0\|_{L^\infty((0,\infty), H^1(\Omega))}$:

$$(4.8) \quad I_3 \leq C \|\varphi_k^e\|_{L^2(\Omega)} \left( \|\varphi_k^e\|_{H^2(\Omega)} + t \right).$$

**Estimating $I_4$.** Setting $r_k^e = \|\left[ P_k, F(0, \cdot) \right](n_k) \|_{L^2(\Omega)}^2$, we have:

$$(4.9) \quad I_4 \leq \|\varphi_k^e\|_{L^2(\Omega)}^2 + r_k^e, \quad \text{and} \quad r_k^e \to 0 \text{ in } L^1(0, T) \text{ for all } T > 0, \text{ with } \varepsilon \text{ fixed.}$$

This is a consequence of the following lemma, the proof of which is postponed to Section 6.2.

**Lemma 4.1.** For all $T > 0$ and $n \in C([0, T], H^2_N(\Omega)) \cap L^2((0, T), H^3(\Omega))$,

$$[P_k, F(0, \cdot)](n) \to 0 \text{ in } L^2((0, T), H^1(\Omega)).$$

**Gathering $L^2$ estimates.** Adding (4.6), (4.7), (4.8) and (4.9), we get

$$(4.10) \quad \frac{\varepsilon}{2} \frac{d}{dt} \left( \|\varphi_k^e\|_{L^2(\Omega)}^2 + \|\nabla \varphi_k^e\|_{L^2(\Omega)}^2 \right) \leq C \|\varphi_k^e\|_{H^2(\Omega)} \left( t + \|\varphi_k^e\|_{H^2(\Omega)} + \|\varphi_k^e\|_{H^2(\Omega)}^2 + r_k^e \right),$$

for some constant depending on the quantities $\|h_{ext}\|_{L^\infty}, \|\partial_t h_{ext}\|_{L^\infty}$ and $\|n_0\|_{L^\infty((0,\infty), H^1(\Omega))}$, and $r_k^e$ from (4.9).
4.1.3 $H^2$ estimates

Next, take the scalar product in $L^2(\Omega)$ of $\Delta^2 \varphi^\varepsilon_k$ with the first equation in (4.5) to get

$$
\varepsilon \frac{d}{dt} \left( \|\Delta \varphi^\varepsilon_k\|_{L^2(\Omega)}^2 \right) + \alpha \|\nabla \Delta \varphi^\varepsilon_k\|_{L^2(\Omega)}^2 = II_1 + II_2 + II_3 + II_4,
$$

with

$$
II_1 = \left( \Delta^2 \varphi^\varepsilon_k \mid m^\varepsilon_k \& (\Delta \varphi^\varepsilon_k + h_d(\varphi^\varepsilon_k)) \right)_{L^2(\Omega)},
$$

$$
II_2 = \alpha \left( \Delta^2 \varphi^\varepsilon_k \mid |\nabla m^\varepsilon_k|^2 m^\varepsilon_k - |\nabla n^\varepsilon_k|^2 n^\varepsilon_k \right)_{L^2(\Omega)},
$$

$$
II_3 = -\alpha \left( \Delta^2 \varphi^\varepsilon_k \mid m^\varepsilon_k \& (m^\varepsilon_k \& (h_d(m^\varepsilon_k) + h_{ext}(t)))
\right.
\left. - n^\varepsilon_k \& (n^\varepsilon_k \& (h_d(n^\varepsilon_k) + h_{ext}(t))) \right)_{L^2(\Omega)},
$$

$$
II_4 = \left( \Delta^2 \varphi^\varepsilon_k \mid [P_k, F(0, \cdot)](\varphi^\varepsilon) \right)_{L^2(\Omega)}.
$$

**Estimating $II_1$.** Split

$$
II_1 = II_{1,1} + II_{1,2} + II_{1,3},
$$

with

$$
II_{1,1} = \left( \Delta^2 \varphi^\varepsilon_k \mid m^\varepsilon_k \& (\Delta \varphi^\varepsilon_k + h_d(\varphi^\varepsilon_k)) \right)_{L^2(\Omega)},
$$

$$
II_{1,2} = \left( \Delta^2 \varphi^\varepsilon_k \mid \varphi^\varepsilon_k \& h_T(t, n^\varepsilon_k) \right)_{L^2(\Omega)},
$$

$$
II_{1,3} = \left( \Delta^2 \varphi^\varepsilon_k \mid n^\varepsilon_k \& (h_{ext}(t) - h_{ext}(0)) \right)_{L^2(\Omega)}.
$$

The first term is written

$$
II_{1,1} = \left( \Delta^2 \varphi^\varepsilon_k \mid n^\varepsilon_k \& (\Delta \varphi^\varepsilon_k + h_d(\varphi^\varepsilon_k)) \right)_{L^2(\Omega)}
+ \left( \Delta^2 \varphi^\varepsilon_k \mid \varphi^\varepsilon_k \& (\Delta \varphi^\varepsilon_k + h_d(\varphi^\varepsilon_k)) \right)_{L^2(\Omega)}.
$$

Integrating by parts,

$$
\left( \Delta^2 \varphi^\varepsilon_k \mid n^\varepsilon_k \& (\Delta \varphi^\varepsilon_k + h_d(\varphi^\varepsilon_k)) \right)_{L^2(\Omega)} =
\left( \nabla \Delta \varphi^\varepsilon_k \mid \nabla n^\varepsilon_k \& (\Delta \varphi^\varepsilon_k + h_d(\varphi^\varepsilon_k)) + n^\varepsilon_k \& \nabla h_d(\varphi^\varepsilon_k) \right)_{L^2(\Omega)}
\leq \eta \|\nabla \Delta \varphi^\varepsilon_k\|_{L^2(\Omega)}^2 + \frac{1}{4 \eta} \|\nabla n^\varepsilon_k \& (\Delta \varphi^\varepsilon_k + h_d(\varphi^\varepsilon_k)) + n^\varepsilon_k \& \nabla h_d(\varphi^\varepsilon_k)\|_{L^2(\Omega)}^2
\leq \eta \|\nabla \Delta \varphi^\varepsilon_k\|_{L^2(\Omega)}^2 + C_\eta \left( \|n^\varepsilon_k\|_{H^2(\Omega)}^2 + \|\nabla n^\varepsilon_k\|_{L^2(\Omega)}^2 \right) \|\varphi^\varepsilon_k\|_{H^2(\Omega)},
$$

where $C_\eta$ is a positive constant.
for all \( \eta > 0 \), for some (large) constant \( C_\eta \), using Sobolev’s inequalities. From this, we deduce that for all \( \eta > 0 \), there exists \( C_\eta > 0 \), depending only on \( \|n_0\|_{L^\infty((0,\infty),H^2(\Omega))} \), such that

\[
(\Delta^2 \varphi_k^\eta | n_k^\eta \wedge (\Delta \varphi_k^\eta + h_d(\varphi_k^\eta)))_{L^2(\Omega)} \leq \eta \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)}^2 + C_\eta \left(1 + \|\nabla \Delta n_k^\eta\|_{L^2(\Omega)}^2\right) \|\varphi_k^\eta\|_{H^2(\Omega)}^2.
\]  

(4.11)

Integrating by parts again,

\[
(\Delta^2 \varphi_k^\eta | \varphi_k^\eta \wedge (\Delta \varphi_k^\eta + h_d(\varphi_k^\eta)))_{L^2(\Omega)} =
\]

\[
- \left(\nabla \Delta \varphi_k^\eta \cdot \nabla \varphi_k^\eta \wedge (\Delta \varphi_k^\eta + h_d(\varphi_k^\eta)) + \varphi_k^\eta \wedge \nabla h_d(\varphi_k^\eta)\right)_{L^2(\Omega)}
\]

\[
\leq \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)} \|\nabla \varphi_k^\eta\|_{L^\infty(\Omega)} \|\Delta \varphi_k^\eta\|_{L^2(\Omega)}
+ \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)} \left(\|\nabla \varphi_k^\eta\|_{L^2(\Omega)} \|h_d(\varphi_k^\eta)\|_{L^4(\Omega)} + \|\varphi_k^\eta\|_{L^1(\Omega)} \|\nabla h_d(\varphi_k^\eta)\|_{L^4(\Omega)}\right)
\]

\[
\leq \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)} \left(\|\nabla \varphi_k^\eta\|_{L^2(\Omega)} + \|\nabla \varphi_k^\eta\|_{L^2(\Omega)} \|\varphi_k^\eta\|_{H^2(\Omega)}
+ \|\nabla \varphi_k^\eta\|_{L^2(\Omega)}^2 \|\varphi_k^\eta\|_{H^2(\Omega)}^2\right),
\]

using \( \|\nabla h_d(\varphi_k^\eta)\|_{L^1(\Omega)} \leq \|h_d(\varphi_k^\eta)\|_{H^2(\Omega)} \leq \|\varphi_k^\eta\|_{H^2(\Omega)} \). Hence, there exists an absolute constant \( C > 0 \), and for all \( \eta > 0 \), there exists \( C_\eta > 0 \) such that

\[
(\Delta^2 \varphi_k^\eta | \varphi_k^\eta \wedge (\Delta \varphi_k^\eta + h_d(\varphi_k^\eta)))_{L^2(\Omega)} \leq (\eta + C \|\varphi_k^\eta\|_{H^2(\Omega)}) \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)}^2 + C_\eta \|\varphi_k^\eta\|_{H^2(\Omega)}^4.
\]  

(4.12)

Summing up (4.11) and (4.12), one gets \( C > 0 \) and, for all \( \eta > 0 \), a constant \( C_\eta > 0 \) (depending on \( \|n_0\|_{L^\infty((0,\infty),H^2(\Omega))} \)) such that

\[
II_{1,1} \leq (\eta + C \|\varphi_k^\eta\|_{H^2(\Omega)}) \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)}^2
+ C_\eta \left(1 + \|\nabla \Delta n_k^\eta\|_{L^2(\Omega)}^2 + \|\varphi_k^\eta\|_{H^2(\Omega)}^2\right) \|\varphi_k^\eta\|_{H^2(\Omega)}^2.
\]  

(4.13)

The second term is

\[
II_{1,2} = - \left(\nabla \Delta \varphi_k^\eta \cdot \nabla \varphi_k^\eta \wedge (\Delta n_k^\eta + h_d(n_k^\eta) + h_{ext}(t))\right)_{L^2(\Omega)}
- \left(\nabla \Delta \varphi_k^\eta \cdot \varphi_k^\eta \wedge (\nabla n_k^\eta + \nabla h_d(\varphi_k^\eta) + \nabla h_{ext}(t))\right)_{L^2(\Omega)}.
\]

Using Sobolev’s inequalities again, we have, for all \( \eta > 0 \), a constant \( C_\eta \) (depending on \( \|n_0\|_{L^\infty((0,\infty),H^2(\Omega))} \) and \( \|h_{ext}\|_{L^\infty(\Omega)} \)) such that

\[
- \left(\nabla \Delta \varphi_k^\eta \cdot \nabla \varphi_k^\eta \wedge (\Delta n_k^\eta + h_d(n_k^\eta) + h_{ext}(t))\right)_{L^2(\Omega)} \leq \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)} \times
\]

\[
\times \left(\|\nabla \varphi_k^\eta\|_{L^2(\Omega)} \|\Delta n_k^\eta + h_d(n_k^\eta)\|_{L^4(\Omega)} + \|\nabla \varphi_k^\eta\|_{L^2(\Omega)} \|h_{ext}(t)\|_{L^\infty(\Omega)}\right)
\]

\[
\leq C \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)} \|\varphi_k^\eta\|_{H^2(\Omega)} \times
\]

\[
\times \left(\|\Delta n_k^\eta\|_{L^2(\Omega)} + \|n_k^\eta\|_{H^2(\Omega)} + \|h_{ext}(t)\|_{L^\infty(\Omega)}\right)
\]

\[
\leq \eta \|\nabla \Delta \varphi_k^\eta\|_{L^2(\Omega)}^2 + C_\eta \left(1 + \|\nabla \Delta n_k^\eta\|_{L^2(\Omega)}^2\right) \|\varphi_k^\eta\|_{H^2(\Omega)}^2.
\]  

(4.14)
In the same way, for all \( \eta > 0 \), there is \( C_\eta > 0 \) (depending on \( \|n_0\|_{L^\infty(0,\infty),H^2(\Omega)} \) and \( \|\nabla h_{\text{ext}}\|_{L^\infty_t H^1_x} \)) such that

\[
- \left( \nabla \Delta \varphi_k^\varepsilon \mid \nabla \Delta n_k^\varepsilon + \nabla h_{\text{ext}}(\varphi_k^\varepsilon + \nabla h_{\text{ext}}(t)) \right) \leq \eta \|\nabla \Delta \varphi_k^\varepsilon\|_{L^2(\Omega)}^2 + C_\eta \left( 1 + \|\nabla \Delta n_k^\varepsilon\|_{L^2(\Omega)}^2 \right) \|\varphi_k^\varepsilon\|_{H^2(\Omega)}^2.
\]

(4.15)

Summing up (4.14) and (4.15), we get, for all \( \eta > 0 \), a constant \( C_\eta > 0 \) (depending on \( \|h_{\text{ext}}\|_{L^\infty_t H^1_x}, \|\nabla h_{\text{ext}}\|_{L^\infty_t H^1_x} \) and \( \|n_0\|_{L^\infty(0,\infty),H^2(\Omega)} \)) such that

\[
II_{1,2} \leq \eta \|\nabla \Delta \varphi_k^\varepsilon\|_{L^2(\Omega)}^2 + C_\eta \left( 1 + \|\nabla \Delta n_k^\varepsilon\|_{L^2(\Omega)}^2 \right) \|\varphi_k^\varepsilon\|_{H^2(\Omega)}^2.
\]

(4.16)

The third term is

\[
II_{1,3} = \left( \Delta^2 \varphi_k^\varepsilon \mid n_k^\varepsilon \wedge (h_{\text{ext}}(t) - h_{\text{ext}}(0)) \right) \|\nabla \Delta \varphi_k^\varepsilon\|_{L^2(\Omega)}^2.
\]

Integrating two times by parts, it is easily estimated, thanks to a constant \( C \) depending on \( \|\partial_t h_{\text{ext}}\|_{L^\infty_t W^{1,\infty}_x} \), as

\[
II_{1,3} \leq C t \|n_k^\varepsilon\|_{H^2(\Omega)} \|\varphi_k^\varepsilon\|_{H^2(\Omega)}.
\]

(4.17)

This gives finally, summing up (4.13), (4.16) and (4.17): there is \( C > 0 \), and for all \( \eta > 0 \), there is \( C_\eta > 0 \) (depending on \( \eta, \|n_0\|_{L^\infty(0,\infty),H^2(\Omega)}, \|h_{\text{ext}}\|_{L^\infty_t W^{1,\infty}_x} \) and \( \|\partial_t h_{\text{ext}}\|_{L^\infty_t W^{2,\infty}_x} \)), such that

\[
II_1 \leq \left( \eta + C \|\varphi_k^\varepsilon\|_{H^2(\Omega)} \right) \|\nabla \Delta \varphi_k^\varepsilon\|_{L^2(\Omega)}^2
+ C_\eta \left( 1 + \|\nabla \Delta n_k^\varepsilon\|_{L^2(\Omega)}^2 + \|\varphi_k^\varepsilon\|_{H^2(\Omega)}^2 \right) \|\varphi_k^\varepsilon\|_{H^2(\Omega)} + t \|\varphi_k^\varepsilon\|_{H^2(\Omega)}.
\]

Estimating \( II_2 \). Split

\[
II_2 = II_{2,1} + II_{2,2},
\]

with

\[
II_{2,1} = \left( \Delta^2 \varphi_k^\varepsilon \mid (|\nabla m_k^\varepsilon|^2 - |\nabla n_k^\varepsilon|^2)(n_k^\varepsilon + \varphi_k^\varepsilon) \right)_{L^2(\Omega)}
+ \left( \partial_\varepsilon \nabla \varphi_k^\varepsilon \mid (\nabla \varphi_k^\varepsilon + 2\nabla n_k^\varepsilon)m_k^\varepsilon \right)_{L^2(\Omega)},
\]

\[
II_{2,2} = \left( \Delta^2 \varphi_k^\varepsilon \mid |\nabla n_k^\varepsilon|^2(m_k^\varepsilon - n_k^\varepsilon) \right)_{L^2(\Omega)}
= \left( \Delta^2 \varphi_k^\varepsilon \mid |\nabla n_k^\varepsilon|^2 \varphi_k^\varepsilon \right)_{L^2(\Omega)}.
\]

Then, using in particular the Sobolev inequality from Lemma 3.2

\[
\|\nabla n_k^\varepsilon\|_{L^\infty(\Omega)} \lesssim \|\nabla \varphi_k^\varepsilon\|_{L^2(\Omega)} + \|\nabla \Delta n_k^\varepsilon\|_{L^2(\Omega)}.
\]
we get:

\[
I_{2,1} = - \left( \nabla \Delta \phi_k^e \mid \Delta \phi_k^e \cdot (\nabla \phi_k^e + 2 \nabla n_k^e)(n_k^e + \phi_k^e) \right)_{L^2(\Omega)}
- \left( \nabla \Delta \phi_k^e \mid \nabla \phi_k^e \cdot (\Delta \phi_k^e + 2 \Delta n_k^e)(n_k^e + \phi_k^e) \right)_{L^2(\Omega)}
- \left( \nabla \Delta \phi_k^e \mid \nabla \phi_k^e \cdot (\nabla \phi_k^e + 2 \nabla n_k^e)(\nabla n_k^e + \nabla \phi_k^e) \right)_{L^2(\Omega)}
\]

\[
\leq \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} \parallel \Delta \phi_k^e \parallel_{L^2(\Omega)} \times
\times \left( \parallel \nabla \phi_k^e \parallel_{L^\infty(\Omega)} + 2 \parallel \nabla n_k^e \parallel_{L^\infty(\Omega)} \right) \left( \parallel n_k^e \parallel_{L^\infty(\Omega)} + \parallel \phi_k^e \parallel_{L^\infty(\Omega)} \right)
+ \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} \parallel \nabla \phi_k^e \parallel_{L^2(\Omega)} \times
\times \left( \parallel \Delta \phi_k^e \parallel_{L^4(\Omega)} + 2 \parallel \Delta n_k^e \parallel_{L^4(\Omega)} \right) \left( \parallel n_k^e \parallel_{L^\infty(\Omega)} + \parallel \phi_k^e \parallel_{L^\infty(\Omega)} \right)
+ \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} \parallel \nabla \phi_k^e \parallel_{L^2(\Omega)} \times
\times \left( \parallel \nabla \phi_k^e \parallel_{L^6(\Omega)} + 2 \parallel \nabla n_k^e \parallel_{L^6(\Omega)} \right) \left( \parallel n_k^e \parallel_{L^\infty(\Omega)} + \parallel \nabla \phi_k^e \parallel_{L^2(\Omega)} \right)
\]

(4.19)

\[
\leq \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} \parallel \phi_k^e \parallel_{H^2(\Omega)} \left( \parallel n_k^e \parallel_{H^2(\Omega)} + \parallel \phi_k^e \parallel_{H^2(\Omega)} \right) \times
\times \left( \parallel \nabla \phi_k^e \parallel_{L^2(\Omega)} + \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} + \parallel \nabla n_k^e \parallel_{L^2(\Omega)} + \parallel \nabla \Delta n_k^e \parallel_{L^2(\Omega)} \right)
+ \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} \parallel \phi_k^e \parallel_{H^2(\Omega)} \left( \parallel n_k^e \parallel_{H^2(\Omega)} + \parallel \phi_k^e \parallel_{H^2(\Omega)} \right) \times
\times \left( \parallel \Delta \phi_k^e \parallel_{L^2(\Omega)} + \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} + \parallel \Delta n_k^e \parallel_{L^2(\Omega)} + \parallel \nabla \Delta n_k^e \parallel_{L^2(\Omega)} \right)
+ \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} \parallel \phi_k^e \parallel_{H^2(\Omega)} \left( \parallel n_k^e \parallel_{H^2(\Omega)} + \parallel \phi_k^e \parallel_{H^2(\Omega)} \right)^2
\]

\[
\leq \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} \parallel \phi_k^e \parallel_{H^2(\Omega)} \left( \parallel n_k^e \parallel_{H^2(\Omega)} + \parallel \phi_k^e \parallel_{H^2(\Omega)} \right) \times
\times \left( \parallel \phi_k^e \parallel_{H^2(\Omega)} + \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)} + \parallel n_k^e \parallel_{H^2(\Omega)} + \parallel \nabla \Delta n_k^e \parallel_{L^2(\Omega)} \right)
\leq \left( \eta + \parallel \phi_k^e \parallel_{H^2(\Omega)} \left( \parallel n_k^e \parallel_{H^2(\Omega)} + \parallel \phi_k^e \parallel_{H^2(\Omega)} \right) \right) \parallel \nabla \Delta \phi_k^e \parallel_{L^2(\Omega)}^2
\]

\[
+ C_\eta \parallel \phi_k^e \parallel_{H^2(\Omega)}^2 \left( \parallel \phi_k^e \parallel_{H^2(\Omega)} + \parallel n_k^e \parallel_{H^2(\Omega)} + \parallel \nabla \Delta n_k^e \parallel_{L^2(\Omega)} \right)^2 \times
\times \left( \parallel n_k^e \parallel_{H^2(\Omega)} + \parallel \phi_k^e \parallel_{H^2(\Omega)} \right)^2,
\]

for all \( \eta > 0 \), for some \( C_\eta > 0 \).
Also, for all $\eta > 0$, there is $C_\eta > 0$ such that
\[
II_{2,2} = - \left( \nabla \Delta \varphi_k^\varepsilon \mid 2 \nabla n_k^\varepsilon \Delta n_k^\varepsilon \varphi_k^\varepsilon \right)_{L^2(\Omega)} - \left( \nabla \Delta \varphi_k^\varepsilon \mid |\nabla n_k^\varepsilon|^2 \nabla \varphi_k^\varepsilon \right)_{L^2(\Omega)} \\
\leq \| \nabla \Delta \varphi_k^\varepsilon \|_{L^2(\Omega)} \left( 2 \| \nabla n_k^\varepsilon \|_{L^\infty(\Omega)} \| \Delta n_k^\varepsilon \|_{L^2(\Omega)} \| \varphi_k^\varepsilon \|_{L^\infty(\Omega)} + \| \nabla \varphi_k^\varepsilon \|_{L^2(\Omega)} \right) \\
+ \| \nabla n_k^\varepsilon \|_{L^2(\Omega)}^2 \| \nabla \varphi_k^\varepsilon \|_{L^2(\Omega)} \\
\lesssim \eta \| \nabla \Delta \varphi_k^\varepsilon \|_{L^2(\Omega)}^2 \\
+ C_\eta \left( \| n_k^\varepsilon \|_{H^2(\Omega)}^2 + \| \nabla n_k^\varepsilon \|_{H^2(\Omega)}^2 + 1 \right) \| n_k^\varepsilon \|_{H^2(\Omega)}^2 \| \varphi_k^\varepsilon \|_{H^2(\Omega)}^2.
\] (4.20)

Summing up (4.19) and (4.20), we get: there is $C > 0$, and for all $\eta > 0$, there is $C_\eta > 0$ (with $C$ and $C_\eta$ depending on $\| n_0 \|_{L^\infty((0,\infty),H^2(\Omega))}$) such that
\[
II_2 \leq C \left( \eta + \| \varphi_k^\varepsilon \|_{H^2(\Omega)} \left( 1 + \| \varphi_k^\varepsilon \|_{H^2(\Omega)} \right) \right) \| \nabla \Delta \varphi_k^\varepsilon \|_{L^2(\Omega)}^2 \\
+ C_\eta \| \varphi_k^\varepsilon \|_{H^2(\Omega)} \left( 1 + \| \varphi_k^\varepsilon \|_{H^2(\Omega)} \right) \left( 1 + \| \varphi_k^\varepsilon \|_{H^2(\Omega)}^2 + \| \nabla n_k^\varepsilon \|_{H^2(\Omega)}^2 \right).
\] (4.21)

**Estimating $II_3$.** Now,
\[
II_3 = II_{3,1} + II_{3,2},
\]
with
\[
II_{3,1} = -\alpha \left( \Delta^2 \varphi_k^\varepsilon \mid m_k^\varepsilon \wedge \left( m_k^\varepsilon \wedge h_d(n_k^\varepsilon) \right) - n_k^\varepsilon \wedge \left( n_k^\varepsilon \wedge h_d(n_k^\varepsilon) \right) \right)_{L^2(\Omega)},
\]
\[
II_{3,2} = -\alpha \left( \Delta^2 \varphi_k^\varepsilon \mid m_k^\varepsilon \wedge \left( m_k^\varepsilon \wedge h_{ext}(t) \right) - n_k^\varepsilon \wedge \left( n_k^\varepsilon \wedge h_{ext}(0) \right) \right)_{L^2(\Omega)}.
\]

Concerning $II_{3,1}$, first write $m_k^\varepsilon = n_k^\varepsilon + \varphi_k^\varepsilon$, then integrate once by parts, so that $II_{3,1}$ takes the form of a $L^2$ scalar product between $\nabla \Delta \varphi_k^\varepsilon$ and a sum of terms $\nabla (abc)$, where $a, b, c$ may be $n_k^\varepsilon$ (or $h_d(n_k^\varepsilon)$) or $\varphi_k^\varepsilon$ (or $h_d(\varphi_k^\varepsilon)$), and at least one of them is $n_k^\varepsilon$ (or $h_d(n_k^\varepsilon)$). Estimating each of $a, b, c$ and their gradients in $L^6$, one gets: for all $\eta > 0$, there is $C_\eta > 0$ such that
\[
II_{3,1} \leq \eta \| \nabla \Delta \varphi_k^\varepsilon \|_{L^2(\Omega)}^2 + C_\eta \left( 1 + \| n_k^\varepsilon \|_{H^2(\Omega)}^2 + \| \varphi_k^\varepsilon \|_{H^2(\Omega)}^2 \right) \| \varphi_k^\varepsilon \|_{H^2(\Omega)}^2.
\] (4.22)

Then, split $II_{3,2}$,
\[
II_{3,2} = -\alpha \left( \Delta^2 \varphi_k^\varepsilon \mid m_k^\varepsilon \wedge \left( m_k^\varepsilon \wedge \left( h_{ext}(t) - h_{ext}(0) \right) \right) \right)_{L^2(\Omega)} \\
- \alpha \left( \Delta^2 \varphi_k^\varepsilon \mid m_k^\varepsilon \wedge \left( m_k^\varepsilon \wedge h_{ext}(0) \right) - n_k^\varepsilon \wedge \left( n_k^\varepsilon \wedge h_{ext}(0) \right) \right)_{L^2(\Omega)}.
\]

The second term is estimated as $II_{3,1}$. The first one is split into a sum involving $n_k^\varepsilon \wedge \left( n_k^\varepsilon \wedge \left( h_{ext}(t) - h_{ext}(0) \right) \right)$, and products of $h_{ext}(t)$ with two terms,
one of them being \( \varphi_k^r \), and the other, \( \varphi_k^l \) or \( n_k^r \). This leads to: for all \( \eta > 0 \), there is \( C_\eta > 0 \) (also depending on \( h_\text{ext} \)) such that

\[
I_{3,2} \leq \eta \|\nabla \Delta \varphi_k^r\|_{L^2(\Omega)}^2 + C_\eta \left( \left( 1 + \|n_k^r\|^2_{H^2(\Omega)} + \|\varphi_k^r\|^2_{H^2(\Omega)} \right) \right)
\]

(4.23)

\[
+ t\|\varphi_k^r\|_{H^2(\Omega)}^2 \|\varphi_k^r\|_{H^2(\Omega)}.
\]

Finally, summing up (4.22) and (4.23), we have: for all \( \eta > 0 \), there is \( C_\eta > 0 \) (depending on \( \|n_0\|_{L^\infty((0,\infty),H^2(\Omega))} \)) such that

\[
II_3 \leq \eta \|\nabla \Delta \varphi_k^r\|_{L^2(\Omega)}^2 + C_\eta \left( \left( 1 + \|\varphi_k^r\|^2_{L^2(\Omega)} \right) \right)
\]

(4.24)

\[
+ t\|\varphi_k^r\|_{H^2(\Omega)}^2 \|\varphi_k^r\|_{H^2(\Omega)}.
\]

**Estimating \( II_4 \).** Integrating once by parts, we get

\[
II_4 = - \left( \nabla \Delta \varphi_k^r \mid \nabla[P_k, F(0, \cdot)](n^\varepsilon) \right)_{L^2(\Omega)}.
\]

Thus, for all \( \eta > 0 \), there exists \( C_\eta > 0 \) such that

\[
II_4 \leq \eta \|\nabla \Delta \varphi_k^r\|_{L^2(\Omega)}^2 + C_\eta r_{k,1}^r,
\]

(4.25)

with

\[
r_{k,1}^r = \|\nabla[P_k, F(0, \cdot)](n^\varepsilon)\|_{L^2(\Omega)}^2 \rightarrow 0 \text{ in } L^\infty(0,T) \text{ for all } T > 0, \text{ with } \varepsilon \text{ fixed,}
\]

thanks to Lemma 4.1.

### 4.1.4 Conclusion

From (4.18), (4.21), (4.24) and (4.25), we deduce that there is a constant \( C > 0 \) (depending on \( \|n_0\|_{L^\infty((0,\infty),H^2(\Omega))} \)), and for all \( \eta > 0 \), there is \( C_\eta > 0 \) (depending on \( \eta, \|n_0\|_{L^\infty((0,\infty),H^2(\Omega))}, \|h_\text{ext}\|_{L^\infty W_{x}^{1,\infty}}, \|\partial_t h_\text{ext}\|_{L^\infty W_{x}^{1,\infty}} \)) such that

\[
\frac{\varepsilon}{2} \frac{d}{dt} \|\Delta \varphi_k^r\|_{L^2(\Omega)}^2
\]

(4.26)

\[
+ \left( \alpha - C(\eta + \|\varphi_k^r\|_{H^2(\Omega)}(1 + \|\varphi_k^r\|_{H^2(\Omega)})) \right) \|\nabla \Delta \varphi_k^r\|_{L^2(\Omega)}^2
\]

\[
\leq C_\eta \left( \|\varphi_k^r\|_{H^2(\Omega)}^2(1 + \|\varphi_k^r\|_{H^2(\Omega)})(1 + \|\varphi_k^r\|_{H^2(\Omega)}^2 + \|\nabla \Delta \varphi_k^r\|_{L^2(\Omega)}^2)
\]

\[
+ t\|\varphi_k^r\|_{H^2(\Omega)} + r_{k,1}^r. \right)
\]

Sum up (4.10) and (4.26), to get: there is a constant \( C > 0 \) (depending on \( \|n_0\|_{L^\infty((0,\infty),H^2(\Omega))} \)), and for all \( \eta > 0 \), there is \( C_\eta > 0 \) (depending on \( \eta, \)
\[\|n_0\|_{L^\infty((0, \infty), H^2(\Omega))}, \|h_{\text{ext}}\|_{L^p_t W^{1,\infty}} \text{ and } \|\partial_t h_{\text{ext}}\|_{L^p_t W^{1,\infty}},\] such that

\[
\frac{\varepsilon}{2} \frac{d}{dt} \left(\|\varphi_k^\varepsilon\|^2_{H^2(\Omega)}\right) + \left(\alpha - C(\eta + \|\varphi_k^\varepsilon\|_{H^2(\Omega)}(1 + \|\varphi_k^\varepsilon\|_{H^2(\Omega)}))\right)\|\nabla \Delta \varphi_k^\varepsilon\|^2_{H^2(\Omega)} \\
\leq C(\|\varphi_k^\varepsilon\|_{H^2(\Omega)}(1 + \|\varphi_k^\varepsilon\|_{H^2(\Omega)})(1 + \|\varphi_k^\varepsilon\|_{H^2(\Omega)} + \|\nabla \Delta n_k^\varepsilon\|^2_{L^2(\Omega)}) \\
+ t\|\varphi_k^\varepsilon\|_{H^2(\Omega)} + \tilde{r}_k^\varepsilon),
\]

with \(\tilde{r}_k^\varepsilon = \| [P_k, F(0,\cdot)](n^\varepsilon) \|^2_{H^1(\Omega)} \to 0\) in \(L^\infty(0, T)\) for all \(T > 0\), with \(\varepsilon\) fixed.

Now, apply the following Gronwall lemma (the proof of which is postponed to Section 6.3).

**Lemma 4.2.** There is a constant \(K > 0\) (depending on \(n_0\) and \(h_{\text{ext}}\)) such that, for all \(c \in (0, 1/K)\), setting \(t_\varepsilon = c\varepsilon \ln(1/\varepsilon)\), there is \(\varepsilon_0 = \varepsilon_0(c, \alpha, c, K)\) such that (4.27) implies:

\[
\forall \varepsilon \in (0, \varepsilon_0], \quad \exists k(\varepsilon) \in \mathbb{N}^+, \quad \forall k \geq k(\varepsilon),
\]

\[
\sup_{[0, t_\varepsilon]} \|\varphi_k^\varepsilon\|^2_{H^2(\Omega)} \leq \left(\frac{\varepsilon^{1-cK}}{K} + K\|\tilde{r}_k^\varepsilon\|_{L^1([0, t_\varepsilon])}\varepsilon^{-1-cK}\right) e^{K\|\nabla \Delta P_k n_0\|^2_{L^2((0, \infty) \times \Omega)}.}
\]

### 4.1.5 Passing to the limit \(k \to \infty\)

For each \(\varepsilon \in (0, \varepsilon_0]\) fixed, by Lemma 4.2, the sequence \((\varphi_k^\varepsilon)_{k \in \mathbb{N}^+}\) is bounded in \(L^\infty((0, t_\varepsilon), H^2(\Omega))\). Equation (4.5) then implies that the sequence \((\partial_t \varphi_k^\varepsilon)_{k \in \mathbb{N}^+}\) is bounded in \(L^\infty((0, t_\varepsilon), L^2(\Omega))\). Furthermore, (4.27) shows that \((\varphi_k^\varepsilon)_{k \in \mathbb{N}^+}\) is also bounded in \(L^2((0, t_\varepsilon), H^3(\Omega))\). Aubin’s Lemma (see [2], [10]) then implies that there is a subsequence of \((\varphi_k^\varepsilon)_{k \in \mathbb{N}^+}\), converging in \(L^2((0, t_\varepsilon), H^2(\Omega))\) towards some \(\varphi^\varepsilon\).

Up to a subsequence, we may assume that \((\partial_t \varphi_k^\varepsilon)_{k \in \mathbb{N}^+}\) also converges weakly in \(L^2((0, t_\varepsilon), L^2(\Omega))\) towards \(\partial_t \varphi^\varepsilon\). As \(k \to \infty\), \(P_k n^\varepsilon\) converges towards \(n^\varepsilon\) in \(C([0, t_\varepsilon], H^2(\Omega)) \cap H^1((0, t_\varepsilon), L^2(\Omega))\). Thus, \((m_k^\varepsilon)_{k \in \mathbb{N}^+}\) converges towards some \(m^\varepsilon\) in \(L^2((0, t_\varepsilon), H^2(\Omega))\), with \((\partial_t m_k^\varepsilon)_{k \in \mathbb{N}^+}\) converging weakly in \(L^2((0, t_\varepsilon), L^2(\Omega))\) towards \(\partial_t m^\varepsilon\). This is enough to pass to the limit in (4.4), so that \(m^\varepsilon\) is solution to (4.2). With \(\varepsilon\) fixed, as well as showing that \(m^\varepsilon\) is continuous in time with values in \(H^2\) is standard, as well as uniqueness and stability properties: see [4], or [1].

Finally, passing to the limit in Lemma 4.2 yields:

\[
\sup_{[0, t_\varepsilon]} \|\varphi^\varepsilon\|^2_{H^2(\Omega)} \leq \frac{\varepsilon^{1-cK}}{K} e^{K\|\nabla \Delta n_0\|^2_{L^2((0, \infty) \times \Omega)}},
\]

which we write

\[
\sup_{[0, t_\varepsilon]} \|\varphi^\varepsilon\|^2_{H^2(\Omega)} \leq K' \varepsilon^{1-cK}.
\]
4.2 Second step: following the slow dynamics after $t_\varepsilon$

From the local-in-time existence result, we know that, for each $\varepsilon \in (0, \varepsilon_0)$, there is $t^\varepsilon > t_\varepsilon$ such that $m^\varepsilon$ exists, as a solution to (4.2), in $C([0, t^\varepsilon], H^2(\Omega)) \cap L^2((0, t^\varepsilon), H^3(\Omega))$. We shall show, via a priori estimates, that $t^\varepsilon \geq T$ (possibly reducing $\varepsilon_0$).

From (3.1), and with $F$ from (4.3), we deduce that, on $[0, T] \times \Omega$,

$$\varepsilon \partial_t m_{eq} - \alpha \Delta m_{eq} = F(t, m_{eq}) + \varepsilon \partial_t m_{eq}. \tag{4.29}$$

Subtracting to (4.2), we get on $[0, t^\varepsilon] \times \Omega$:

$$\begin{cases}
(\varepsilon \partial_t - \alpha \Delta)(m^\varepsilon - m_{eq}) = (\mathcal{L}(m_{eq}) + \mathcal{R}(m_{eq}))(m^\varepsilon - m_{eq}) + \varepsilon \partial_t m_{eq}, \\
\partial_x(m^\varepsilon - m_{eq})|_{\partial\Omega} = 0,
\end{cases} \tag{4.30}$$

and we consider the associated Cauchy problem with data given at time $t_\varepsilon$. The data at time $t_\varepsilon = c\varepsilon \ln(1/\varepsilon)$ satisfy (using (4.28) and (4.1)):

$$\|m^\varepsilon(t) - m_{eq}(t)\|_{H^2(\Omega)} \leq \|m^\varepsilon(t) - n^\varepsilon(t)\|_{H^2(\Omega)} + \|n^\varepsilon(t) - m_{eq}(0)\|_{H^2(\Omega)}$$

$$+ \|m_{eq}(0) - m_{eq}(t)\|_{H^2(\Omega)}$$

$$\leq K\varepsilon^{1-cK} + \|n_0(c\ln(1/\varepsilon)) - m_{eq}(0)\|_{H^2(\Omega)}$$

$$+ \|m_{eq}(0) - m_{eq}(t)\|_{H^2(\Omega)} \xrightarrow{\varepsilon \to 0} 0.$$

Here, for all $\delta \in H^2(\Omega)$ and $t \in [0, T]$,

$$\mathcal{L}(t, m_{eq}(t)) \delta = \alpha |\nabla m_{eq}(t)|^2 \delta + 2\alpha \left(\nabla m_{eq}(t) \cdot \nabla \delta \right) m_{eq}(t)$$

$$+ \delta \land h_T(t, m_{eq}(t)) + m_{eq}(t) \land \left(\Delta \delta + h_d(\delta)\right)$$

$$- \alpha \delta \land \left(h_d(m_{eq}(t)) + h_{ext}(t)\right)$$

$$- \alpha m_{eq}(t) \land \left(\delta \land \left(h_{d}(m_{eq}(t)) + h_{ext}(t)\right)\right)$$

$$- \alpha m_{eq}(t) \land \left(m_{eq}(t) \land h_d(\delta)\right), \tag{4.31}$$

and

$$\mathcal{R}(t, m_{eq}(t)) \delta = 2\alpha \left(\nabla m_{eq}(t) \cdot \nabla \delta \right) \delta + \alpha |\nabla \delta|^2 \delta + \delta \land \left(\Delta \delta + h_d(\delta)\right)$$

$$- \alpha \delta \land \left(h_d(m_{eq}(t)) + h_{ext}(t)\right) - \alpha \delta \land \left(m_{eq}(t) \land h_d(\delta)\right)$$

$$- \alpha m_{eq}(t) \land \left(\delta \land h_d(\delta)\right) - \alpha \delta \land \left(h_d(\delta)\right). \tag{4.32}$$

In the sequel, we consider

$$\delta^\varepsilon := m^\varepsilon - m_{eq} \in C([0, t^\varepsilon], H^2(\Omega)) \cap L^2((0, t^\varepsilon), H^3(\Omega)).$$
and we simply prove that in \((H^2)^*\) energy estimates, the term due to the residual \(\mathcal{R}(m_{eq})\delta^v\) is dominated by the terms due to \(\alpha \Delta \delta^v\) and to the linear term \(\mathcal{L}(m_{eq})\delta^v\). We thus come back to the Galerkin approximation \(\delta^v_k\) of \(\delta^v\), as in Paragraph 4.1.1. Take the \(L^2(\Omega)\) scalar product of the equations with \(\delta^v_k\) and \(\Delta^2 \delta^v_k\) and integrate by parts. Estimating \((\delta^v_k \mid \mathcal{R}(m_{eq})(\delta^v_k))_{L^2(\Omega)}\) is straightforward. Due to the continuity properties of \(h_d\) on Sobolev spaces, \((\Delta^2 \delta^v_k \mid \mathcal{R}(m_{eq})(\delta^v_k))_{L^2(\Omega)}\) produces three kinds of terms. Dropping the exponent \(\varepsilon\) and subscript \(k\) (and using the notation \(L(v_1, \ldots, v_n)\) for any \(n\)-linear application), we examine each of them.

From \(\delta \wedge (\delta \wedge h_d(\delta))\). We have

\[
(\Delta^2 \delta \mid L(\delta, \delta, \delta))_{L^2(\Omega)} = \| \Delta \delta \|_{L^2(\Omega)} \| \mathcal{L}(\delta, \delta, \delta) \|_{L^2(\Omega)},
\]

which is bounded from above by \(C\|\delta\|_{H^2(\Omega)}^4\), since \(H^2(\Omega)\) is an algebra.

In the same way, the terms of the form \((\Delta^2 \delta \mid L(\delta, \delta))_{L^2(\Omega)}\) are controlled by \(|\delta|_{H^2(\Omega)}^3\). This rules out the terms from \(\delta \wedge h_d(\delta), \delta \wedge (h_d(m_{eq}(t)) + h_{ext}(t))\), \(\delta \wedge (m_{eq}(t) \wedge h_d(\delta))\) and \(m_{eq}(t) \wedge (\delta \wedge h_d(\delta))\).

From \(|\nabla \delta|^2 \delta\). Write

\[
(\Delta^2 \delta \mid L(\nabla \delta, \nabla \delta, \delta))_{L^2(\Omega)} = - (\nabla \Delta \delta \mid L(\nabla \delta, \nabla \delta, \nabla \delta))_{L^2(\Omega)} - (\nabla \Delta \delta \mid \mathcal{L}(\nabla \delta, \nabla \delta, \delta))_{L^2(\Omega)}.
\]

Then,

\[
|\nabla \Delta \delta |_{L^2(\Omega)} \leq \| \nabla \Delta \delta \|_{L^2(\Omega)} \| L(\nabla \delta, \nabla \delta, \nabla \delta) \|_{L^2(\Omega)} \leq C \| \nabla \Delta \delta \|_{L^2(\Omega)} \| \nabla \delta \|_{L^2(\Omega)},
\]

and by Sobolev’s inequalities, \(\|\nabla \delta\|_{L^2(\Omega)}\) is controlled by \(\|\delta\|_{H^2(\Omega)}\).

Also,

\[
|\nabla \Delta \delta \mid \mathcal{L}(\nabla \delta, \nabla \delta, \delta))_{L^2(\Omega)} \leq C \| \nabla \Delta \delta \|_{L^2(\Omega)} \| \Delta \delta \|_{L^2(\Omega)} \| \nabla \delta \|_{L^2(\Omega)} \| \delta \|_{L^2(\Omega)}.
\]

From the estimate

\[
\| \nabla \delta \|_{L^2(\Omega)} \leq \| \nabla \delta \|_{L^2(\Omega)} + \| \nabla \Delta \delta \|_{L^2(\Omega)},
\]

we get

\[
|\nabla \Delta \delta \mid \mathcal{L}(\nabla \delta, \nabla \delta, \delta))_{L^2(\Omega)} \leq C (\| \nabla \Delta \delta \|_{L^2(\Omega)} \| \delta \|_{H^2(\Omega)}^3 + \| \nabla \Delta \delta \|_{L^2(\Omega)}^2 \| \delta \|_{H^2(\Omega)}^2).
\]

This leads to

\[
(\Delta^2 \delta \mid L(\nabla \delta, \nabla \delta, \delta))_{L^2(\Omega)} \leq C \| \nabla \Delta \delta \|_{L^2(\Omega)} \| \delta \|_{H^2(\Omega)}^3 + \| \nabla \Delta \delta \|_{L^2(\Omega)}^2 \| \delta \|_{H^2(\Omega)}^2.
\]

In the same way, we have

\[
(\Delta^2 \delta \mid (\nabla m_{eq}(t) \cdot \nabla) \delta) \leq C \| \nabla \Delta \delta \|_{L^2(\Omega)} \| \delta \|_{H^2(\Omega)}^2.
\]
The $\delta \land \Delta \delta$ term. Again,

$$(\Delta^2 \delta \mid L(\delta, \Delta \delta))_{L^2(\Omega)} = -(\nabla \Delta \delta \mid L(\nabla \delta, \Delta \delta))_{L^2(\Omega)} - (\nabla \Delta \delta \mid L(\delta, \nabla \Delta \delta))_{L^2(\Omega)},$$

and as above, we get

$$(\Delta^2 \delta \mid L(\delta, \Delta \delta))_{L^2(\Omega)} \leq C(\|\nabla \Delta \delta\|_{L^2(\Omega)}^2 + \|\nabla \Delta \delta\|_{L^2(\Omega)}^2) + \|\nabla \Delta \delta\|_{L^2(\Omega)}^2 ||H^2(\Omega)||^2.$$

Finally, there is $C > 0$, and for all $\eta > 0$, there is $C_\eta > 0$ such that

$$(\delta_k^\varepsilon \mid R(m_{eq})(\delta_k^\varepsilon))_{H^2(\Omega)} \leq \left(\eta + C(1 + \|\delta_k^\varepsilon\|_{H^2(\Omega)})\|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 + C_\eta\right)\|\Delta \delta_k^\varepsilon\|_{L^2(\Omega)}^2 \leq C_\eta\|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 + \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2.$$

Let $k$ go to infinity, so that the above estimate applies to $\delta_k^\varepsilon$ instead of $\delta_k^\varepsilon$, up to the local existence time $t^\varepsilon$ obtained via the convergence of the Galerkin scheme. Coming back to (4.29), still with $\delta_k^\varepsilon = m^\varepsilon - m_{eq}$, we get, using (2.5): there is $C > 0$, and for all $\eta > 0$, there is $C_\eta > 0$ such that

$$(4.33) \frac{\varepsilon}{2} \frac{d}{dt} \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 + \alpha \eta - C(1 + \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2)\|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 \|\nabla \delta_k^\varepsilon\|_{H^2(\Omega)}^2 \leq C_\eta(1 + \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2)^3 \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 - C_{\text{lin}} \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 + \varepsilon^2 \|\partial_t m_{eq}\|_{H^2(\Omega)}^2.$$

As in the proof of Lemma 4.2, fix $\eta \in (0, \alpha)$, and consider the time $\tilde{t} \leq t^\varepsilon$ up to which, in (4.33), the parenthesis in front of $\|\nabla \delta_k^\varepsilon\|_{H^2(\Omega)}^2$ (resp. $\|\delta_k^\varepsilon\|_{H^2(\Omega)}^2$) remains positive (resp. less than $-C_{\text{lin}}/2$). We have, for $t \in (t_\varepsilon, \tilde{t})$:

$$\frac{\varepsilon}{2} \frac{d}{dt} \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 \leq \frac{C_{\text{lin}}}{2} \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 + \varepsilon^2 \|\partial_t m_{eq}\|_{H^2(\Omega)}^2.$$

Gronwall’s lemma then implies that

$$\sup_{[t_\varepsilon, \tilde{t}]} \|\delta_k^\varepsilon\|_{H^2(\Omega)}^2 \leq \|\delta_k^\varepsilon(t_\varepsilon)\|_{H^2(\Omega)}^2 + \varepsilon^2 T \sup_{[0, T]} \|\delta_k^\varepsilon(t)\|_{H^2(\Omega)}^2,$$

so that, for $\varepsilon$ small enough, we get $\tilde{t} \geq T$, and $\sup_{[t_\varepsilon, T]} \|\delta_k^\varepsilon\|_{H^2(\Omega)} \to 0$. This finishes the proof of Theorem 2.1. \hfill \Box

5 Proof of Proposition 2.2 and Corollary 2.3

Proof of Proposition 2.2. For any $T > 0$ and $n \in C([0, T], H^2(\Omega))$, it is equivalent for $n$ to be solution to (2.8) or to

$$(\partial_t - \alpha \Delta)(n - m_{eq}) = \left(L(0, m_{eq}) + R(0, m_{eq})\right)(n - m_{eq}),$$

22
with the same initial and boundary conditions. The operators $L(0, m_{\text{eq}})$ and $R(0, m_{\text{eq}})$ from (4.31) and (4.32) do not depend on time, now. Arguing as in Section 4.2, we get an estimate analogue to (4.33),

$$
\begin{align*}
\frac{1}{2} \frac{d}{dt} \left( \| \n - m_{\text{eq}} \|^2_{H^2(\Omega)} \right) + \left( \alpha - \eta - C(1 + \| \n - m_{\text{eq}} \|_{H^2(\Omega)}) \| \n - m_{\text{eq}} \|^2_{H^2(\Omega)} \right) \| \nabla (\n - m_{\text{eq}}) \|^2_{H^2(\Omega)} \\
\leq C_\eta (1 + \| \n - m_{\text{eq}} \|_{H^2(\Omega)})^3 \| \n - m_{\text{eq}} \|_{H^2(\Omega)} - C_{\text{lin}} \| \n - m_{\text{eq}} \|^2_{H^2(\Omega)}.
\end{align*}
$$

Once $\eta \in (0, \alpha/2)$ is chosen, take $\eta_0 > 0$ such that, when $\| \m_0 - m_{\text{eq}} \|_{H^2(\Omega)} \leq \eta_0$, the parentheses in front of $\| \nabla (\n - m_{\text{eq}}) \|^2_{H^2(\Omega)}$ and in front of $\| \n - m_{\text{eq}} \|^2_{H^2(\Omega)}$ are positive and negative at $t = 0$, respectively. The bootstrap argument then shows that $\n \in C([0, \infty), H^2(\Omega))$, and that $\n(t)$ converges in $H^2(\Omega, S^2)$, as $t$ goes to $\infty$, towards $m_{\text{eq}}(t_0)$:

$$
(5.1) \quad \| \n(t) - m_{\text{eq}} \|_{H^2(\Omega)} \leq \eta_0 e^{-Ct},
$$

for some $C \in (0, C_{\text{lin}})$ depending on $\eta_0$. Coming back to (5.1), we see also that $\nabla (\n - m_{\text{eq}}) \in L^2((0, \infty), H^2(\Omega))$. □

**Proof of Corollary 2.3.** When $m_{\text{eq}}(0)$ is constant over $\Omega$, Proposition 2.2 ensures there exists some $\eta_0 > 0$ such that for all $\m_0 \in H^2_N(\Omega, S^2)$ satisfying

$$
\| \m_0 - m_{\text{eq}} \|_{H^2(\Omega)} \leq \eta_0,
$$

Asumption (ii) in Theorem 2.1 holds true. Furthermore, estimations (5.1) and (5.2) show that the corresponding function $\n_0$ has norms in $L^\infty((0, \infty), H^2(\Omega))$ and in $L^2((0, \infty) \times \Omega)$ controlled in terms of $m_{\text{eq}}(0)$ and $\eta_0$ only. Thus, $\varepsilon_0$ in the proof of Theorem 2.1 may also be chosen depending on $m_{\text{eq}}(0)$ and $\eta_0$ only, uniformly with respect to $\m_0$. □

6 Appendix

6.1 About the dissipation property (2.5): proof of Lemmas 3.5 and 3.6

Let $\delta \in C([0, T], H^\infty(\Omega))$ be such that $|m_{\text{eq}} + \delta| \equiv 1$ and $\partial_{\nu} \delta|_{\partial \Omega} = \partial_{\nu} \Delta \delta|_{\partial \Omega} = 0$. Then,

$$
\mathcal{L}(m_{\text{eq}}^\pm) \delta = (\lambda \mp d) \delta \wedge u \pm u \wedge (\Delta \delta + h_d(\delta)) + \alpha (d \mp \lambda) u \wedge (\delta \wedge u) - \alpha u \wedge (u \wedge h_d(\delta)).
$$
6.1.1 \( L^2 \) estimates

Take the \( L^2(\Omega) \) scalar product of (6.1) with \( \delta \). This yields

\[
(\mathcal{L}(m_{eq}^\pm \delta \mid \delta))_{L^2(\Omega)} = \pm \int_{\Omega} \delta \cdot (u \wedge \Delta \delta) \pm \int_{\Omega} \delta \cdot (u \wedge h_d(\delta)) + \alpha(d \mp \lambda) \int_{\Omega} |\delta \wedge u|^2 - \alpha \int_{\Omega} (u \cdot h_d(\delta)) (u \cdot \delta) + \alpha \int_{\Omega} \delta \cdot h_d(\delta).
\]

(6.2)

First consider the case of \( m_{eq}^+ \). Denoting \( n \) the exterior normal vector to \( \Omega \), the first term in the right-hand side of (6.2) is equal to

\[
(\mathcal{L}(m_{eq}^+ \delta \mid \delta))_{L^2(\Omega)} = \sum_{i=1}^{3} \int_{\Omega} \delta \cdot \partial_i(u \wedge \partial_i \delta) = \sum_{i=1}^{3} \int_{\partial \Omega} \delta \cdot (u \wedge \partial_i \delta)n_i = \int_{\partial \Omega} \delta \cdot (u \wedge \partial_n \delta) = 0.
\]

(6.3)

Since \( h_d \) is continuous on \( L^2 \) with norm 1, the second term is bounded from above by \( \|\delta\|_{L^2(\Omega)}^2 \). Similarly, due to the non-positivity of \( h_d \), the last term is non-positive. In the two other terms, we inject the identities

\[
|\delta|^2 = -2u \cdot \delta \quad \text{and} \quad |\delta \wedge u|^2 = |\delta|^2 - \frac{1}{4} |\delta|^4,
\]

(6.4)

which stem from the equality \( |u + \delta| \equiv 1 \). This leads to

\[
(\mathcal{L}(m_{eq}^+) \delta \mid \delta))_{L^2(\Omega)} \leq \|\delta\|_{L^2(\Omega)}^2 + \alpha(d - \lambda) \int_{\Omega} (|\delta|^2 - |\delta|^4/4) + \frac{\alpha}{2} \int_{\Omega} (u \cdot h_d(\delta)) |\delta|^2 = (1 + \alpha(d - \lambda)) \|\delta\|_{L^2(\Omega)}^2 + O(\|\delta\|_{L^2(\Omega)}^3),
\]

(6.5)

In the case of \( m_{eq}^- \), we obtain in the same way

\[
(\mathcal{L}(m_{eq}^-) \delta \mid \delta))_{L^2(\Omega)} \geq (\alpha(\lambda + d) - c) \|\delta\|_{L^2(\Omega)}^2 + O(\|\delta\|_{L^2(\Omega)}^3),
\]

(6.6)

for some constant \( c \) depending on \( \Omega \) and \( \alpha \) only.

6.1.2 \( H^2 \) estimates

Take the \( L^2(\Omega) \) scalar product of the Laplacian of each term in (6.1) with \( \Delta \delta \). This yields

\[
(\Delta \mathcal{L}(m_{eq}^\pm \delta \mid \Delta \delta))_{L^2(\Omega)} = (\lambda \mp d) \int_{\Omega} \Delta \delta \cdot \Delta (\delta \wedge u) \pm \int_{\Omega} \Delta \delta \cdot \Delta (u \wedge \Delta \delta) \pm \int_{\Omega} \delta \cdot \Delta (u \wedge h_d(\delta)) + \alpha(d \mp \lambda) \int_{\Omega} |\Delta \delta \wedge u|^2 - \alpha \int_{\Omega} \Delta \delta \cdot \Delta (u \wedge (u \wedge h_d(\delta))).
\]

(6.7)
Since \(\Delta(\delta \wedge u) = (\Delta \delta) \wedge u = 0\), the first term on the right-hand side vanishes. So does the second one, by the same argument as in (6.3). The equality \(|u + \delta| \equiv 1\) implies
\[
|\Delta \delta \wedge u|^2 = |\Delta \delta|^2 - (|\nabla \delta|^2 - (\delta \cdot \Delta \delta)^2) ,
\]
so that (6.7) gives, for \(m_{eq}^+\):
\[
(\Delta \mathcal{L}(m_{eq}^+) \delta | \Delta \delta)_{L^2(\Omega)} \leq -\alpha(\lambda - d)\|\Delta \delta\|_{L^2(\Omega)}^2 + c\|\delta\|_{H^2(\Omega)}^2 + \mathcal{O}\left(\|\delta\|_{H^2(\Omega)}^3\right) ,
\]
for some constant \(c\) depending on \(\Omega\) and \(\alpha\) only. Together with (6.5), we get finally
\[
(\mathcal{L}(m_{eq}^+) \delta | \delta)_{H^2(\Omega)} \leq - (\alpha(\lambda - d) - c)\|\delta\|_{H^2(\Omega)}^2 + \mathcal{O}\left(\|\delta\|_{H^2(\Omega)}^3\right) ,
\]
which concludes the proof of Lemma 3.5.

In the case of \(m_{eq}\), we have
\[
(\Delta \mathcal{L}(m_{eq}) \delta | \Delta \delta)_{L^2(\Omega)} = -\int_{\Omega} \Delta \delta \cdot \Delta(u \wedge h_d(\delta)) + \alpha(\lambda + d)\|\Delta \delta\|_{L^2(\Omega)}^2
- \alpha\int_{\Omega} \Delta \delta \cdot \Delta(u \wedge (u \wedge h_d(\delta))) + \mathcal{O}\left(\|\delta\|_{H^2(\Omega)}^3\right) ,
\]
which, together with (6.6), leads to Lemma 3.6.

6.2 Proof of the commutator lemma 4.1

Writting
\[
[P_k, \mathcal{F}(0, \cdot)](n) = (P_k - 1)\mathcal{F}(0, n) + \mathcal{F}(0, n) - \mathcal{F}(0, P_k n) ,
\]
the result follows from the convergence of \(P_k\) towards 1 pointwise as an operator on \(H^1(\Omega)\) (which rules out the term \((P_k - 1)\mathcal{F}(0, n)\)) as well as on \(H^2(\Omega)\), combined (to deal with \(\mathcal{F}(0, n) - \mathcal{F}(0, P_k n)\)) with the continuity of \(\mathcal{F}(0, \cdot)\) from \(C([0, T], H^2(\Omega))\) to \(L^2([0, T], H^1)\) and of Sobolev’s embeddings, implying that \(H^2(\Omega)\) is an algebra (so that all applications \(n \mapsto n \wedge h_d(n), n \mapsto n \wedge (n \wedge h_d(n)), n \mapsto n \wedge h_{ext}(0), n \mapsto n \wedge (n \wedge h_{ext}(0))\) are continuous on \(L^\infty([0, T], H^2(\Omega))\)), and that the product operation maps \(H^2 \times H^1\) to \(H^1\), so that \(n \mapsto n \wedge \Delta n\) and \(n \mapsto |\nabla n|^2 n\) are continuous from \(L^\infty([0, T], H^2(\Omega))\) to \(L^2([0, T], H^3)\) to \(L^2([0, T], H^1)\).

6.3 Proof of Gronwall’s lemma 4.2

First, consider \(k \in \mathbb{N}^*\) and \(\varepsilon > 0\) fixed. Set \(\phi(t) = \|\varphi_k\|_{H^2(\Omega)}^2, r(t) = \tilde{r}_k(t), N_0(t) = \|\nabla P_k n_0(t)\|_{L^2(\Omega)}^2\) and \(N^\varepsilon(t) = \|\nabla n^\varepsilon_k(t)\|_{L^2(\Omega)}^2\), so that
\[
N^\varepsilon(t) = N_0(t/\varepsilon) \quad \text{and} \quad N_0 \in L^1(0, \infty).
\]
With $C$ from (4.27), choose $\eta \in (0, \alpha/(2C))$. Hence, there exists $\kappa_\eta \in (0, 1)$ such that
\[
\forall \varphi \in [0, \kappa_\eta], \quad C(\eta + \varphi(1 + \varphi)) < \alpha/2.\]
Set $K = 8C_\eta$ (also from (4.27)), $c \in (0, 1/K)$ and $t_\varepsilon = c\varepsilon \ln(1/\varepsilon)$. Then, with
\[
t_k^\varepsilon = \sup\{t \in [0, t_\varepsilon] \mid \forall t' \in [0, t], \phi'(t') \leq \kappa_\eta\}
\]
($t_k^\varepsilon > 0$ since $\phi^\varepsilon(0) = 0$), we have:
\[
\forall t \in [0, t_k^\varepsilon], \quad \varepsilon\phi^\varepsilon(t) \leq K((1 + N^\varepsilon(t))\phi^\varepsilon(t) + t + r(t)).
\]

From this, we deduce:
\[
\forall t \in [0, t_k^\varepsilon], \quad \phi^\varepsilon(t) \leq \int_0^t \frac{K}{\varepsilon} \left(t' + r(t')\right) \exp\left(\frac{K}{\varepsilon} \int_{t'}^t (1 + N^\varepsilon(t'')) dt''\right) dt'
\]
\[
\leq \left(\int_0^t \frac{K}{\varepsilon} \left(t' + r(t')\right) \exp\left(\frac{K}{\varepsilon} t' - t\right) dt'\right) e^{K\|N_0\|_{L^1(0,\infty)}}
\]
\[
\leq \left(\frac{\varepsilon}{K} + \frac{K}{\varepsilon} \|r\|_{L^1(0,T_0)}\right) e^{Kt/\varepsilon} e^{K\|N_0\|_{L^1(0,\infty)}},
\]
with $T_0 = c\varepsilon_0 \ln(1/\varepsilon_0)$ (and $\varepsilon_0$ is chosen below). Now, since $c \in (0, 1/K)$ and $t_\varepsilon = c\varepsilon \ln(1/\varepsilon)$,
\[
\forall t \in [0, \min(t_k^\varepsilon, t_\varepsilon)], \quad \phi^\varepsilon(t) \leq \left(\frac{\varepsilon^{1-cK}}{K} + K\|r\|_{L^1(0,T_0)}\varepsilon^{1-cK}\right) e^{K\|N_0\|_{L^1(0,\infty)}},
\]
which is less or equal to $\kappa_\eta$ as soon as $\varepsilon$ belongs to $(0, \varepsilon_0]$, for
\[
\varepsilon_0 = \left(\frac{1}{2}\kappa_\eta Ke^{-K\|N_0\|_{L^1(0,\infty)}}\right)^{1/(1-cK)},
\]
and $k$ greater than $K(\varepsilon)$ such that
\[
\forall k \geq K(\varepsilon), \quad \|\tilde{r}_k^\varepsilon\|_{L^1(0,T_0)} \leq \frac{1}{2}\kappa_\eta \varepsilon^{1+cK} e^{-K\|N_0\|_{L^1(0,\infty)}} (which is possible by Lemma 4.1). For this choice of $\varepsilon$ and $k$, we thus have $t_k^\varepsilon \geq t_\varepsilon$, and the result follows. \qed

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