Canonical coordinates with tame estimates for the
defocusing NLS equation on the circle

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Abstract. In a case study for integrable PDEs, we construct real analytic, canonical coordinates for the
defocusing NLS equation on the circle, specifically tailored towards the needs in perturbation theory. They
are defined in neighbourhoods of families of finite dimensional invariant tori and are shown to satisfy together
with their derivatives tame estimates. When expressed in these coordinates, the dNLS Hamiltonian is in
normal form up to order three.

Keywords: defocusing NLS equation, integrable PDEs, normal form.

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Contents

1 Introduction 1

2 Hamiltonian setup 6

3 The map ΨL 9

4 The symplectic corrector ΨC 14

5 Proof of Theorem 1.2 21

6 Proof of Theorem 1.3 33

7 Appendix A: a version of the Poincaré lemma 34

8 Appendix B: formulas for \( d\Psi_{nls}(z_S,0)[(0,z_\perp)] \) 35

1 Introduction

In form of a case study for integrable PDEs, the goal of this paper is to construct canonical coordinates for
the defocusing NLS (dNLS) equation, specifically tailored to the needs in perturbation theory. We consider
the dNLS equation in one space dimension

\[
i\partial_t u = -\partial_x^2 u + 2|u|^2 u, \quad x \in \mathbb{T} := \mathbb{R}/\mathbb{Z}
\]

(1.1)
on the Sobolev space \( H^s_\mathbb{C} \equiv H^s(\mathbb{T}, \mathbb{C}) \) of complex valued functions on \( \mathbb{T} \), whose distributional derivatives
up to order \( s \in \mathbb{Z}_{\geq 0} \) are in \( L^2(\mathbb{T}, \mathbb{C}) \). Equation (1.1) can be viewed as a Hamiltonian PDE, obtained by

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restricting the Hamiltonian system on the phase space \( H_c^s := H_e^s \times H_c^s \) with Poisson bracket and Hamiltonian given by

\[
\{ F, G \}(u, v) = -i \int_0^1 (\partial_u F \partial_v G - \partial_u F \partial_v G) dx, \quad \mathcal{H}^{nls}(u, v) = \int_0^1 (\partial_x u \partial_x v + u^2 v^2) dx \tag{1.2}
\]

to the real subspace \( H^s_c \) of \( H^s \) consisting of elements \((u, v)\) with \( v = \overline{u} \). Here \( F, G \) are \( C^1 \)-smooth complex valued functionals on \( H^s_c \) with sufficiently regular \( L^2 \)-gradients. Equation (1.2) can then be rewritten as \( \partial_t u = -i \partial_x \mathcal{H}^{nls} |_{u=\overline{u}} \). The dNLS equation is an integrable PDE and according to [9], admits global Birkhoff coordinates on \( H^s_c \) with \( s \in \mathbb{Z}_{\geq 0} \). To state the main results of this paper we first need to describe these coordinates in more detail: for any \( s \in \mathbb{Z}_{\geq 0} \), let

\[
h^s_c \equiv h^s(Z, \mathbb{C}) := \{ x = (x_n)_{n \in \mathbb{Z}} \subseteq \mathbb{C} : \|x\|_s < +\infty \}, \quad \|x\|_s := \sum_{n \in \mathbb{Z}} \langle n \rangle^{2s} |x_n|^2, \quad \langle n \rangle := \max\{1, |n|\},
\]

and define the following version \( F_{nls} \) of the Fourier transform, introduced in [12],

\[
F_{nls} : \mathcal{H}^0_c \to h^0_c, \quad (u, v) \mapsto \left( -\frac{1}{\sqrt{2}} (u_n + v_n), -\frac{i}{\sqrt{2}} (u_n - v_n) \right), \tag{1.3}
\]

where \( u_n \) denotes the \( n \)th Fourier coefficient of \( u \), \( u_n := \int_0^1 u(x) e^{-2\pi i n x} dx \). Note that for \( v = \overline{u} \), one has \( v_n = \overline{u}_{-n} \) for any \( n \in \mathbb{Z} \), implying that

\[
F_{nls}(u, \overline{u}) = \left( -\sqrt{2} \text{Re}(u_{-n}), \sqrt{2} \text{Im}(u_{-n}) \right).
\]

The inverse of \( F_{nls} \) is then given by

\[
F^{-1}_{nls} : h^0_c \to \mathcal{H}^0_c, \quad ((x_n)_{n \in \mathbb{Z}}, (y_n)_{n \in \mathbb{Z}}) \mapsto \left( -\frac{1}{\sqrt{2}} \sum_{n \in \mathbb{Z}} (x_n - iy_n) e^{2\pi i n x}, -\frac{1}{\sqrt{2}} \sum_{n \in \mathbb{Z}} (x_n + iy_n) e^{2\pi i n x} \right).
\]

Finally we recall that a possibly nonlinear map \( F : U \to Y \) of a subset \( U \) of a Banach space \( X \) into another Banach space \( Y \) is said to be bounded if \( F(V) \) is bounded for any bounded subset \( V \) in \( U \).

**Theorem 1.1** ([9], [12]). There exists a neighborhood \( \mathcal{W} \) of \( H^0_c \) in \( H^0_c \) and an analytic map

\[
\Phi^{nls} : \mathcal{W} \to h^0_c, \quad (u, v) \mapsto ((x_n)_{n \in \mathbb{Z}}, (y_n)_{n \in \mathbb{Z}})
\]

with \( \Phi^{nls}(0) = 0 \) such that the following holds:

(B1) For any \( s \in \mathbb{Z}_{\geq 0} \), \( \Phi^{nls} : H^s_c \subseteq h^s_c \) and \( \Phi^{nls} : H^s_c \to h^s_c \) is a real analytic diffeomorphism.

(B2) The map \( \Phi^{nls} \) is canonical, meaning that on \( \mathcal{W} \), \( (x_n, y_n) = -1 \) and all the other brackets between coordinate functions vanish.
In particular, in [2] they were used to show the existence of finite dimensional invariant tori of large size for the dNLS equation.

(B3) The Hamiltonian \( H^{nls} := H^{nls} \circ (\Phi^{nls})^{-1} \), defined on \( h^1_r \), is a function of the actions \( I_n := (x_n^2 + y_n^2)/2 \), \( n \in \mathbb{Z} \), only and \( H^{nls} : l^1_r^{1,2} \to \mathbb{R}, I \mapsto H^{nls}(I) \) is real analytic.

(B4) The differential \( d_0 \Phi^{nls} \) of \( \Phi^{nls} \) at 0 is the Fourier transform \( F^{nls} \) defined in [1.3].

(B5) The nonlinear parts \( A^{nls} := \Phi^{nls} - F^{nls} \) of \( \Phi^{nls} \) and \( B^{nls} := \Psi^{nls} - F^{-1}_{nls} \) of \( \Psi^{nls} := (\Phi^{nls})^{-1} \) are one smoothing, meaning that for any \( s \in \mathbb{Z}_{\geq 1} \),

\[
A^{nls} : h^s_r \to h^{s+1}_r \quad \text{and} \quad B^{nls} : h^s_r \to h^{s+1}_r
\]

are real analytic and bounded.

The maps \( \Phi^{nls}, \Psi^{nls} \) are referred to as Birkhoff maps and the coordinates \( (x_n, y_n) \in \mathbb{Z} \) as Birkhoff coordinates for the dNLS equation.

Birkhoff coordinates are a tool to study perturbations of the dNLS equation far away from the equilibrium. In particular, in [2] they were used to show the existence of finite dimensional invariant tori of large size for Hamiltonian perturbations of this equation, involving no derivatives of \( u \). So far, no such results have been obtained for perturbations involving \( \partial_s u \) (and possibly \( \partial_s^2 u \)) — see [2, 11, 12, 13, 15] for results on perturbations of the dNLS equation on the circle obtained so far. In view of the recent results in [11] concerning the existence of small quasi-periodic solutions of quasi-linear Hamiltonian perturbations of the KdV equation and our results in [2] described above, we expect that Hamiltonian perturbations of the dNLS equation, involving \( \partial_s u \) (and possibly \( \partial_s^2 u \)), also admit large quasi-periodic solutions, also referred to as multi-solitons. For this purpose, the scheme developed in [2] has to be considerably refined. In particular, canonical coordinates are needed which together with their derivatives satisfy tame estimates. In [17], such estimates were derived for \( \Phi^{nls} \) and its inverse, but so far are not available for their derivatives. In this paper, we prove how to use the Birkhoff coordinates to construct near bounded, integrable, finite dimensional subsystems of the dNLS equation, local canonical coordinates so that they satisfy tame estimates and the dNLS Hamiltonian, when expressed in these coordinates, is in normal form up to order three — see Theorem 1 for a precise statement. In future work, we will use these coordinates as a starting point for applying a KAM scheme to reduce certain linear operators with tame estimates, which come up in the Nash Moser iteration, to operators with constant coefficients. Recently, such schemes have been further developed in significant ways. In the context of the dNLS equation, results of this type in [3] will be particularly relevant.

To state our main result, we need to introduce some more notation. For any \( S \subseteq \mathbb{Z} \) with \( |S| < +\infty \), let \( S^\perp := \mathbb{Z} \setminus S \). By a slight abuse of notation, we identify \( h^s(S^\perp, \mathbb{C}) \times h^s(S, \mathbb{C}) \) and \( h^s(S^\perp, \mathbb{R}) \times h^s(S, \mathbb{R}) \).

Accordingly, an element \( z \in h^0_0 \) is written as

\[
z = (zs, z_\perp), \quad zs = ((x_j)_{j \in S}, (y_j)_{j \in S}), \quad z_\perp = ((x_j)_{j \in S^\perp}, (y_j)_{j \in S^\perp}),
\]

and as norm we choose \( ||z||_s := ||zs|| + ||z_\perp||_s \) where

\[
||zs|| \equiv ||zs||_0 := \left( \sum_{j \in S} |x_j|^2 + |y_j|^2 \right)^{\frac{1}{2}}, \quad ||z_\perp||_s := \left( \sum_{j \in S^\perp} (j)^2(|x_j|^2 + |y_j|^2) \right)^{\frac{1}{2}}.
\]

Furthermore, we introduce the bilinear form

\[(z_\perp, z_\perp')_r := \sum_{j \in S^\perp} x_j x_j' + y_j y_j', \quad z = (x, y), \quad z_\perp = (x_\perp, y_\perp), \quad z'= (x', y') \in h^s_{\perp}.
\]

and write the sequence of actions \( I = (I_k)_{k \in \mathbb{Z}} \) as \( (I_S, I_\perp) \) where

\[
I_S := (I_k)_{k \in S}, \quad I_\perp := (I_k)_{k \in S^\perp}, \quad I_k \equiv I_k(z) = \frac{|z_k|^2}{2} = \frac{x_k^2 + y_k^2}{2}, \quad \forall k \in \mathbb{Z}.
\]
Finally, we introduce the dNLS frequencies
\[ \omega_n^{\text{dNLS}}(I) := \partial_{t_k} H_n^{\text{dNLS}}(I), \quad k \in \mathbb{Z}. \]  

(1.5)

They satisfy asymptotics of the form \( \omega_k(I) = 4k^2 \pi^2 + O(1) \) as \( k \to \pm \infty \). More precisely, the map
\[ \ell^{1,2}_+ \to \mathbb{R}^\infty, \quad (I_k)_{k \in \mathbb{Z}} \mapsto (\omega_n^{\text{dNLS}}(I) - 4\pi^2 n^2)_{n \in \mathbb{Z}} \]

is real analytic and bounded – see Proposition 5.3 in Subsection 5.2 below. The main result of this paper is the following one.

**Theorem 1.2.** Let \( S \subseteq \mathbb{Z} \) be finite. For any compact subset \( K \subseteq \mathbb{R}^S \times \mathbb{R}^S \), there exists an open, bounded, complex neighbourhood \( V \subseteq h_0^S \) of \( K \times \{0\} \) and a bounded analytic map 
\[ \Psi : V \to H_0^S, \quad (z_n)_{n \in \mathbb{Z}} \mapsto w \]

so that the following holds:

(C1) For any \( s \in \mathbb{Z}_{\geq 0}, \) \( \Psi(V \cap h_s^\ast) \subseteq H_s^0 \) and \( \Psi : V \cap h_s^\ast \to H_s^0 \) is a real analytic diffeomorphism onto its image.

(C2) \( \Psi \) is canonical, meaning that on \( \Psi(V \cap h_s^\ast), \) \( \{x_n, y_n\} = -1 \) for any \( n \in \mathbb{Z}, \) whereas all the other brackets between coordinate functions vanish.

(C3) The transformation \( \Psi \) is related to \( \Psi^{\text{nls}} = (\Phi^{\text{nls}})^{-1} \) by
\[ \Psi \mid_{K \times \{0\}} = \Psi^{\text{nls}} \mid_{K \times \{0\}}, \quad d\Psi(z) = d\Psi^{\text{nls}}(z), \quad \forall z \in K \times \{0\}. \]

(C4) The Hamiltonian \( \mathcal{H} := \mathcal{H}^{\text{nls}} \circ \Psi, \) defined on \( V \cap h_1^\ast, \) is in normal form up to order three. More precisely,
\[ \mathcal{H}(z) = H^{\text{nls}}(I_0, 0) + \sum_{n \in \mathbb{Z}^S} \omega_n^{\text{nls}}(I_0, 0) I_n(z) + \mathcal{P}_3(z) \]

where the Hamiltonian \( \mathcal{P}_3 : V \cap h_0^0 \to \mathbb{R} \) is real analytic. Furthermore, \( \mathcal{P}_3 \) satisfies the following tame estimates: for any \( s \in \mathbb{Z}_{\geq 0}, \) \( z \in V \cap h_s^\ast, \) \( \hat{z} \in h_s^\ast, \)
\[ \|\nabla \mathcal{P}_3(z)\|_s \lesssim_s \|z_\perp\|_s \|z_\parallel\|_0, \quad \||d
\nabla \mathcal{P}_3(z)(\hat{z})||_s \lesssim_s \|z_\perp\|_s \|\hat{z}\|_0 + \|z_\parallel\|_0 \|\hat{z}\|_s \]

and for any \( k \in \mathbb{Z}_{\geq 2}, \) \( \hat{z}_1, \ldots, \hat{z}_k \in h_s^\ast,
\[ \|d^k \nabla \mathcal{P}_3(z)(\hat{z}_1, \ldots, \hat{z}_k)\|_s \lesssim_s \sum_{j=1}^k \|\hat{z}_j\|_s \|z_\parallel\|_0 + \|z_\perp\|_0 \|\hat{z}_j\|_s \]

(1.6)

Here, the meaning of \( \lesssim_s \) is the standard one. So e.g. \( \|\nabla \mathcal{P}_3(z)\|_s \lesssim_s \|z_\perp\|_s \|z_\parallel\|_0 \) says that there exists a constant \( C \equiv C(s) > 0 \) so that
\[ \|\nabla \mathcal{P}_3(z)\|_s \leq C \|z_\perp\|_s \|z_\parallel\|_0, \quad \forall z \in V \cap h_s^\ast. \]

(C5) The nonlinear maps
\[ B := \Psi - F^{\text{nls}} : V \cap h_0^0 \to H_0^0 \quad \text{and} \quad A := \Psi^{-1} - F^{\text{nls}} : \Psi(V) \cap H_0^0 \to h_0^0 \]

are real analytic maps and so is
\[ A : V \cap h_0^0 \to \mathcal{L}(H_0^0, h_0^0), \quad z \mapsto A(z) := d\Psi(z)^{-1} - F^{\text{nls}}. \]

On \( V \cap h_0^0, \) the maps \( B \) and \( A \) satisfy the following estimates: for any \( z \in V \cap h_0^0, \) \( k \in \mathbb{Z}_{\geq 1}, \) \( \hat{z}_1, \ldots, \hat{z}_k \in h_0^0, \) and \( w \in H_0^0, \)
\[ \|B(z)\|_0 \lesssim 1, \quad \|d^k B(z)(\hat{z}_1, \ldots, \hat{z}_k)\|_0 \lesssim_k \prod_{j=1}^k \|\hat{z}_j\|_0, \]

4
\[ \|A(z)[\tilde{w}]\|_0 \lesssim \|\tilde{w}\|_0, \quad \|d^k(A(z)[\tilde{w}])[\tilde{z}_1, \ldots, \tilde{z}_k]\|_0 \lesssim_k \|\tilde{w}\|_0 \prod_{j=1}^k \|\tilde{z}_j\|_0. \]

Furthermore, \(B\) is one smoothing, meaning that for any \(s \in \mathbb{Z}_{\geq 1}\), \(B : V \cap h^*_c \to h^{s+1}_c\) is real analytic, and satisfies the following tame estimates: for any \(k \in \mathbb{Z}_{\geq 1}\), \(z \in V \cap h^*_c\), and \(\tilde{z}_1, \ldots, \tilde{z}_k \in h^*_c\),

\[ \|B(z)\|_{s+1} \lesssim_s 1 + \|z\|_s, \quad \|d^kB(z)[\tilde{z}_1, \ldots, \tilde{z}_k]\|_{s+1} \lesssim_{s,k} \sum_{j=1}^k \|\tilde{z}_j\|_s \prod_{i \neq j} \|\tilde{z}_i\|_0 + \|z\|_s \prod_{j=1}^k \|\tilde{z}_j\|_0. \]

Similarly, the maps \(A\) and \(\mathcal{A}\) are one smoothing, meaning that for any \(s \in \mathbb{Z}_{\geq 1}\), \(A : \Psi(V \cap h^*_c) \to h^{s+1}_c\) and \(\mathcal{A} : \mathcal{V} \cap h^*_c \to \mathcal{L}(H^*_c, h^{s+1}_c)\) are real analytic. Moreover, \(A\) satisfies the following tame estimates: for any \(z \in \mathcal{V} \cap h^*_c\), \(\tilde{w} \in H^*_c\),

\[ \|A(z)[\tilde{w}]\|_{s+1} \lesssim_s \|z\|_s \|\tilde{w}\|_0 + \|\tilde{w}\|_s \]

and for any \(k \in \mathbb{Z}_{\geq 1}\), \(\tilde{z}_1, \ldots, \tilde{z}_k \in h^*_c\),

\[ \|d^k(A(z)[\tilde{w}])[\tilde{z}_1, \ldots, \tilde{z}_k]\|_{s+1} \lesssim_{s,k} \left( \|z\|_s \|\tilde{w}\|_0 + \|\tilde{w}\|_s \right) \prod_{j=1}^k \|\tilde{z}_j\|_0 + \|\tilde{w}\|_0 \sum_{j=1}^k \|\tilde{z}_j\|_s \prod_{i \neq j} \|\tilde{z}_i\|_0. \]

**Remark 1.1.** Note that in Theorem 1.2, apart from being compact, no further assumptions on \(K\) are being made. In particular, \(K\) may contain the equilibrium point 0 in which case \(K\) does not admit action-angle coordinates. In subsequent work, the estimates for \(A(z) = d\Psi(z)^{-1} - F_{nls}\) will be used to study perturbations of the dNLS equation. Since such estimates are not needed for \(A(\Psi(z))\), we have not included them in Theorem 1.2.

**Outline of the construction of \(\Psi\):** Let \(V\) be of the form \(V = V_S \times V_\perp \subset h^0\) where \(V_S\) is a bounded, open neighborhood of \(K\) in \(C^S \times C^S\) and \(V_\perp\) an open ball in \(h^0\), centered at \(\{0\}\). By Theorem 1.1, \(V_S\) and \(V_\perp\) can be chosen so that the Birkhoff map \(\Psi^{nls}\) is defined on \(V\) and all the estimates of \(\Psi^{nls}\) and its derivatives used in the sequel are uniform on \(V\). The canonical map \(\Psi\) is then defined to be the composition \(\Psi := \Psi_L \circ \Psi_C\), where \(\Psi_L\) is the Taylor expansion of \(\Psi^{nls}\) of order one in the normal directions \(z_\perp\) around \((z_s, 0)\),

\[ \Psi_L(z_S, z_\perp) := \Psi^{nls}(z_S, 0) + d\Psi^{nls}(z_S, 0)[0, z_\perp], \tag{1.7} \]

and \(\Psi_C\), referred to as symplectic corrector, is chosen so that \(\Psi_L \circ \Psi_C\) becomes symplectic and satisfies the claimed tame estimates.

In his pioneering work [14], Kuksin presents a general scheme for proving KAM type theorems for semilinear Hamiltonian perturbations of integrable PDEs in one space dimension, such as the Korteweg de Vries (KdV) or the sine Gordon (sG) equations, which possess a Lax pair formulation and admit finite dimensional integrable subsystems, foliated by invariant tori. One of the key elements of his work is a normal form theory for such PDEs. Expanding on work of Krichever [13], Kuksin considers bounded integrable finite dimensional subsystems (ISS) of such an integrable PDE (iPDE) which admit action-angle coordinates. In the case of the KdV and the sG equations, the angle variables are given by the celebrated Its Matveev formulas. These action-angle coordinates are complemented by infinitely many coordinates whose construction is based on a set of time periodic solutions, referred to as Floquet solutions, of the partial differential equation obtained by linearizing iPDE along solutions in ISS. The resulting coordinate transformation, denoted in [14] by \(\Phi\), is typically not symplectic and to obtain canonical coordinates, an additional coordinate transformation needs to be applied. In [14], Kuksin constructs such a transformation, which he denotes by \(\phi\), using arguments of Moser and Weinstein in the given infinite dimensional setup – see [14], Lemma 1.4 and Section 7.1. To construct the map \(\Psi_C\) we follow the same scheme of proof. Actually, the following result holds.
Theorem 1.3. Assume that in addition to the assumptions made in Theorem 1.2 the set $K$ is contained in $(\mathbb{R} \setminus 0)^S \times (\mathbb{R} \setminus 0)^S$. Then, up to normalizations and natural identifications, $\Psi_L$ coincides with the map $\Phi$, obtained by applying the scheme of construction in [14] to the dNLS equation. As a consequence, so does $\Psi = \Psi_L \circ \Psi_C$ with $\Phi \circ \phi$.

Since Birkhoff coordinates provide a concise, self-contained, and efficient framework for proving Theorem 1.2 - in particular the claimed tame estimates, the main goal of our study - Theorem 1.3 also provides in the case of the dNLS equation a valuable alternative for proving the normal form result for this equation, obtained by applying the scheme of proof in [14]. Note also that the assumptions on $K$ in Theorem 1.2 are slightly weaker than the ones made in the setup of [14].

Organization: The maps $\Psi_L$ and $\Psi_C$ are introduced and studied in Sections 3 and 1, respectively, after a short Section 2 describing the Hamiltonian setup. In Section 5 we prove Theorem 1.2; in Subsection 5.1 we show that the composition $\Psi = \Psi_L \circ \Psi_C$ satisfies the analytic properties, stated in Theorem 1.2, and in the subsequent Subsection 5.2 the expansion of the dNLS Hamiltonian in the new coordinates is computed up to order three. In Subsection 5.3 we summarize the proof of Theorem 1.2. Finally, in Section 6 we prove Theorem 1.3. In Appendix A, we recall an infinite dimensional version of the Poincaré Lemma, needed in Section 4 (cf from [14], [16]).

Notation: For any $C^1$ map $F : h_0^0 \to X$ with $X$ being a Banach space, we denote by $d_z F(z)$ the differential of $F$ at $z$ with respect to the variable $z$, $d_z F(z)[\tilde{z}] = \sum_{j \in S^c} \hat{x}_j \partial_{x_j} F(z) + \hat{y}_j \partial_{y_j} F(z) = \tilde{z} \in h_0^0$, where for any $j \in S^c$, $\partial_{x_j} F, \partial_{y_j} F \in X$ denote the partial derivatives of $F$ with respect to the variables $x_j$ respectively $y_j$. Similarly, we define the gradient with respect to the variable $z$ as $\nabla_z := ((\partial_{x_j} F)_{j \in S^c}, (\partial_{y_j} F)_{j \in S^c})$.

The gradient of $F$ with respect to $z_S$ is denoted by $\nabla_S F := ((\partial_{x_j} F)_{j \in S}, (\partial_{y_j} F)_{j \in S})$ and the differential of $F$ at $z$ with respect to $z_S$ by $d_S F(z)$, $d_S F(z)[\tilde{z}_S] = \sum_{j \in S} \hat{x}_j \partial_{x_j} F(z) + \hat{y}_j \partial_{y_j} F(z) = \tilde{z}_S \in \mathbb{C}^S \times \mathbb{C}^S$.

For the partial derivatives of $F$ with respect to $z_j$, $j \in S$, we use the multi-index notation and write for any $\alpha, \beta \in \mathbb{Z}_{\geq 0}^S$\n
$$\partial_{S}^{\alpha, \beta} F := \left( \prod_{j \in S} \partial_{x_j}^{\alpha_j} \partial_{y_j}^{\beta_j} \right) F.$$ 

If not stated otherwise, $K$ denotes a compact subset of $\mathbb{R}^S \times \mathbb{R}^S$ and $\mathcal{V}$ an open, bounded neighborhood of $K \times \{0\}$ in $h_0^0$ of the form $\mathcal{V}_S \times S_\perp$, where $\mathcal{V}_S$ is a ball in $h_{\perp}$, centered at 0. We write $\mathcal{V}_S(\delta)$ to indicate that the radius of the ball $\mathcal{V}_S$ is $\delta > 0$. Finally, we frequently will use the symbols $\lesssim, \lesssim_S, \ldots$, to express that a quantity is bounded up to another one up to a constant which is 'universal', respectively depends only on the Sobolev index $s$. E.g., given two real valued functionals $A, B$ on $\mathcal{V}$ we write $A \lesssim_S B$ if there is a constant $C \equiv C(s)$ so that $A(z) \leq CB(z)$ for any $z \in \mathcal{V} \cap h_0^s$.

2 Hamiltonian setup

In this preliminary section we discuss the Hamiltonian setup, introduced in Section 1, in more detail and introduce some additional notations.
The Hamiltonian vector field associated to a sufficiently smooth functional \( F : H^0_c \to \mathbb{C} \) and the Poisson bracket \( \{,\} \) on \( H^0_c \) is denoted by

\[
X_F = \iota [\nabla F, \nabla F] := (\nabla_u F, \nabla_v F)
\]

where \( \nabla_u F, \nabla_v F \) denote the \( L^2 \) gradients with respect to \( u \) and \( v \), namely

\[
dF[\hat{u}, 0] = \int_T \nabla_u F \hat{u} \, dx, \quad dF[0, \hat{v}] = \int_T \nabla_v F \hat{v} \, dx,
\]

\[
\mathbb{J} := \begin{pmatrix} 0 & -1d \Id \\ \Id & 0 \end{pmatrix} : H^0_c \to H^0_c,
\]

and \( \Id : H^0_c \to H^0_c \) is the identity operator. Furthermore we introduce the non degenerate bilinear form

\[
\langle \cdot, \cdot \rangle_r : H^0_c \times H^0_c \to \mathbb{C}
\]

defined for any \( w = (u, v), w' = (u', v') \in H^0_c \) by

\[
\langle w, w' \rangle_r := \int_T u(x) u'(x) \, dx + \int_T v(x) v'(x) \, dx.
\]

The subscript \( r \) indicates that in the latter integrals, no complex conjugation appears. The Poisson bracket then reads

\[
\{ F, G \} = \langle \nabla F, \iota [\nabla G] \rangle_r
\]

and the symplectic form, associated to it, is the two form

\[
\Lambda[\hat{w}, \hat{w}'] := -i(\mathbb{J}^{-1} \hat{w}, \hat{w}')_r = i(\mathbb{J} \hat{w}, \hat{w}')_r = i \int_T (\hat{w}' - \hat{v}') \, dx, \quad \forall \hat{w} = (\hat{u}, \hat{v}), \hat{w}' = (\hat{u}', \hat{v}') \in H^0_c.
\]

For any sufficiently smooth functionals \( F, G : H^0_c \to \mathbb{C} \), one has

\[
\Lambda(X_F, X_G) = \{ F, G \}.
\]

In terms of the Fourier coefficients of \( \hat{w} \) and \( \hat{w}' \), \( \Lambda[\hat{w}, \hat{w}'] \) can be expressed as

\[
\Lambda[\hat{w}, \hat{w}'] = i \sum_{k \in \mathbb{Z}} (\hat{u}_k \hat{v}'_{-k} - \hat{v}_k \hat{u}'_{-k})
\]

and hence \( \Lambda \) can be conveniently written as

\[
\Lambda = i \sum_{k \in \mathbb{Z}} du_k \wedge dv_{-k},
\]

where

\[
(du_k \wedge dv_{-k})[\hat{u}, \hat{v}], (\hat{u}', \hat{v}')] = \hat{u}_k \hat{v}'_{-k} - \hat{v}_k \hat{u}'_{-k}, \quad \forall k \in \mathbb{Z}.
\]

In addition, we define the one form \( \lambda \) on \( H^0_c \) as

\[
\lambda \equiv \lambda(w) = i \sum_{k \in \mathbb{Z}} u_k dv_{-k}.
\]

Its action on a function \( \hat{w} = (\hat{u}, \hat{v}) \in H^0_c \) is given by

\[
\lambda[\hat{w}] = i \int_T u(x) \hat{v}(x) \, dx = i \sum_{k \in \mathbb{Z}} u_k \hat{v}_{-k}.
\]

The exterior differential of \( \lambda \), defined by \( d\lambda = i \sum_{k \in \mathbb{Z}} du_k \wedge dv_{-k} \), thus satisfies \( d\lambda = \Lambda \).
The Poisson bracket on the model space \( h_c^0 \) is determined by defining it for the coordinate functions, 
\[
{x_n, y_m}_M = -\delta_{nm}, \quad {y_n, x_m}_M = \delta_{nm}, \quad {x_n, x_m}_M = 0, \quad {y_n, y_m}_M = 0, \quad \forall n, m \in \mathbb{Z}.
\]
By a slight abuse of terminology in connection with the definition (1.4), we also denote by \( (\cdot, \cdot)_r \) the non-degenerate bilinear form 
\[
(z, z')_r := x \cdot x' + y \cdot y', \quad \forall z = (x, y), \quad z' = (x', y') \in h_c^0.
\]
where \( x \cdot x' := \sum_{k \in \mathbb{Z}} x_k x'_k \). Given two sufficiently smooth functionals \( F, G : h_c^0 \to \mathbb{C} \), one has
\[
\{F, G\}_M = -\sum_k \left( \partial_{x_k} F \partial_{y_k} G - \partial_{y_k} F \partial_{x_k} G \right) = (\nabla F, J \nabla G)_r,
\]
where
\[
J := \begin{pmatrix} 0 & -\text{Id} \\ \text{Id} & 0 \end{pmatrix} : h_c^0 \to h_c^0,
\]
\( \text{Id} : h_c^0 \to h_c^0 \) is the identity operator and
\[
\nabla F = (\nabla_x F, \nabla_y F), \quad \nabla_x F = (\partial_{x_k} F)_{k \in \mathbb{Z}}, \quad \nabla_y F = (\partial_{y_k} F)_{k \in \mathbb{Z}}.
\]
The Hamiltonian vector field \( X_F \) of \( F : h_c^0 \to \mathbb{C} \), corresponding to the Poisson bracket \( \{\cdot, \cdot\}_M \), is then given by
\[
X_F = J \nabla F
\]
and the symplectic form \( \Lambda_M \), associated to it, by
\[
\Lambda_M[z, z'] := (J^{-1}z, z')_r = \hat{y} \cdot \hat{x}' - \hat{x} \cdot \hat{y}', \quad \forall z = (\hat{x}, \hat{y}), \quad z' = (\hat{x}', \hat{y}') \in h_c^0.
\]
Note that
\[
\Lambda_M = -\sum_{k \in \mathbb{Z}} dx_k \wedge dy_k
\]
where as above, for any \( k \in \mathbb{Z} \), the two form \( dx_k \wedge dy_k \) is defined as
\[
(dx_k \wedge dy_k)[(\hat{x}, \hat{y}), (\hat{x}', \hat{y}')] = \hat{x}_k \hat{y}' - \hat{y}_k \hat{x}'.
\]
Then
\[
\Lambda_M(X_F, X_G) = (\nabla F, J \nabla G)_r = \{F, G\}_M.
\]
The one form associated to \( \Lambda_M \) is defined as
\[
\lambda_M \equiv \lambda_M(z) := \sum_{k \in \mathbb{Z}} y_k dx_k.
\]
Its action on a vector \( \hat{z} = (\hat{x}, \hat{y}) \in h_c^0 \) is given by
\[
\lambda_M[\hat{z}] = \sum_{k \in \mathbb{Z}} y_k \hat{x}_k.
\]
The exterior differential of \( \lambda_M \) then satisfies \( d\lambda_M = \Lambda_M \).
3 The map $\Psi_L$

In this section, we study the map $\Psi_L$ introduced in (1.1). In particular, we prove tame estimates and one smoothing properties for $\Psi_L$. First we introduce some more notations. Denote by $\Pi_S$ and $\Pi_\perp$ the standard projections

$$
\Pi_S : (C^S \times C^S) \times h_0^\perp \rightarrow (C^S \times C^S) \times \{ 0 \}, \ z = (z_S, z_\perp) \mapsto (z_S, 0) \quad (3.1)
$$

$$
\Pi_\perp : (C^S \times C^S) \times h_0^\perp \rightarrow \{ 0 \} \times h_0^\perp, \ z = (z_S, z_\perp) \mapsto (0, z_\perp). \quad (3.2)
$$

The formula (1.1) for $\Psi_L(z)$ with $z = (z_S, z_\perp)$ then reads

$$
\Psi_L(z) = \Psi^{nls}(\Pi_S z) + d_1 \Psi^{nls}(\Pi_S z)[z_\perp]. \quad (3.3)
$$

For a quite explicit formula for $d_1 \Psi^{nls}(\Pi_S z)[z_\perp]$, we refer to Appendix B. The map $\Psi_L$ is defined on

$$
V^{\max} := V_S^{\max} \times h_0^\perp, \quad V_S^{\max} := \Pi_S \Phi^{nls}(W)
$$

where $W \subseteq H^0_c$ is the domain of definition of the Birkhoff map $\Phi^{nls}$ of Theorem 1.1. Note that the latter expression is independent of $\Pi_\perp z$.

Furthermore, the differential $d \Psi_L(z)$ of $\Psi_L$ at $z = (z_S, z_\perp) \in V^{\max}$ applied to a vector $\tilde{z} = (\tilde{z}_S, \tilde{z}_\perp) \in h_0^\perp$ is given by

$$
d\Psi_L(z)[\tilde{z}_S, \tilde{z}_\perp] = d_2 \Psi^{nls}(\Pi_S z)[\tilde{z}_S] + d_1 \Psi^{nls}(\Pi_S z)[\tilde{z}_\perp] + d_S(d_1 \Psi^{nls}(\Pi_S z)[z_\perp])[\tilde{z}_S] + d_S(d_1 \Psi^{nls}(\Pi_S z)[z_\perp])[\tilde{z}_\perp] \quad (3.4)
$$

$$
= d\Psi^{nls}(\Pi_S z)[\tilde{z}] + d^2 \Psi^{nls}(\Pi_S z)[\tilde{z}_S, \tilde{z}_\perp, \Pi_S z, \Pi_\perp z]. \quad (3.5)
$$

Note that the latter expression is independent of $\Pi_\perp \tilde{z}$ and that by Theorem 1.1, $d \Psi_L(0) = d \Psi^{nls}(0) = F^{-1}_{nls}$. First we establish the following auxiliary results.

**Lemma 3.1.** (i) The map $\Psi_L : V^{\max} \rightarrow H^0_c$ is analytic and for any $s \in \mathbb{Z}_{\geq 0}$, the restriction $\Psi_L|_{h^s_r} : h^s_r \rightarrow H^s_c$ is real analytic. Furthermore, for any $z_S \in \mathbb{R}^S \times \mathbb{R}^S$ and any $s \in \mathbb{Z}_{\geq 0}$, $d \Psi_L(z_S, 0) : h^s_c \rightarrow H^s_c$ is a linear isomorphism.

(ii) For any compact subset $K \subseteq \mathbb{R}^S \times \mathbb{R}^S$, there exists a ball $V_\perp$ in $h_0^\perp$, centered at 0, so that the restriction $\Psi_L : K \times V_\perp \rightarrow H_0^0$ is one to one. Furthermore, after shrinking the radius of the ball $V_\perp$, if necessary, the map $\Psi_L : K \times V_\perp \rightarrow H_0^0$ is a local diffeomorphism.

**Proof.** (i) The claimed analyticity follows from the definition of $\Psi_L$ and the corresponding properties of $\Psi^{nls}$, stated in Theorem 1.1. Concerning the statement on the differential $d \Psi_L(z_S, 0)$, note that by (3.3), $d \Psi_L(z_S, 0) = d \Psi^{nls}(z_S, 0)$ and hence by Theorem 1.1, $d \Psi_L(z_S, 0) : h^s_c \rightarrow H^s_c$ is a linear isomorphism for any $s \in \mathbb{Z}_{\geq 0}$.

(ii) Let $K \subseteq \mathbb{R}^S \times \mathbb{R}^S$ be given compact subset. Assume that there exists no ball $V_\perp$ in $h_0^\perp$, centered at 0, so that $\Psi_L|_{K \times V_\perp}$ is 1-1. Then there exist two sequences $z^{(j)} = (z_S^{(j)}, z_\perp^{(j)})_j \geq 1$, and $\tilde{z}^{(j)} = (\tilde{z}_S^{(j)}, \tilde{z}_\perp^{(j)})_j \geq 1$, with $z^{(j)} \neq \tilde{z}^{(j)}$, $\Psi_L(z^{(j)}) = \Psi_L(\tilde{z}^{(j)})$, $\lim_{j \rightarrow \infty} z_S^{(j)} = \lim_{j \rightarrow \infty} \tilde{z}_S^{(j)} = 0$, $\lim_{j \rightarrow \infty} z_\perp^{(j)} = \lim_{j \rightarrow \infty} \tilde{z}_\perp^{(j)} = 0$.

Since by assumption $K$ is compact, there exist subsequences of $(z^{(j)})_{j \geq 1}, (\tilde{z}^{(j)})_{j \geq 1}$, denoted for simplicity in the same way, such that $(z_S^{(j)})_{j \geq 1}, (\tilde{z}_S^{(j)})_{j \geq 1}$ converge. Denote their limits by $z_S^{(\infty)}$ and $\tilde{z}_S^{(\infty)}$, respectively. Then

$$
\lim_{j \rightarrow \infty} z^{(j)} = (z_S^{(\infty)}, 0), \quad \lim_{j \rightarrow \infty} \tilde{z}^{(j)} = (\tilde{z}_S^{(\infty)}, 0)
$$

are elements in $K \times \{ 0 \}$. By the continuity of $\Psi_L$, one has $\Psi_L(z_S^{(\infty)}, 0) = \Psi_L(\tilde{z}_S^{(\infty)}, 0)$ and since $\Psi_L$ and $\Psi^{nls}$ coincide on $V^{\max} \times \{ 0 \}$ it then follows from Theorem 1.1 that $z_S^{(\infty)} = \tilde{z}_S^{(\infty)}$. By item (i) and the local inversion theorem one then concludes that in contradiction to our assumption, $z^{(j)} = \tilde{z}^{(j)}$ for $j$ sufficiently large. This proves the first part of item (ii). Since according to item (i), for any given $z_S \in K$, $d \Psi_L(z_S, 0) : h^0_c \rightarrow H^0_c$ is a linear isomorphism, $d \Psi_L(z)$ is such an operator for $z$ in a whole neighborhood of $(z_S, 0)$. Using that $K$ is compact it then follows that after shrinking the radius of the ball $V_\perp$, if necessary, $\Psi_L : K \times V_\perp \rightarrow H_0^0$ is a local diffeomorphism. □
Proposition 3.1. For any compact subset $K \subseteq \mathbb{R}^S \times \mathbb{R}^S$ there exists an open complex neighbourhood $V$ of $K \times \{0\}$ in $h_0^c$ of the form $V_S \times V_L$ where $\nabla_S$ is compact with $\nabla_S \subseteq \nabla_S^{\max}$ and $V_L \subset h_0^{0c}$ is an open ball, centered at 0, so that the restriction of $\Psi_L$ to $V$ has the following properties:

(L1) $\Psi_L$ is analytic on $V$ and

$$\Psi_L |_{V_S \times \{0\}} = \Psi^{nls} |_{V_S \times \{0\}}, \quad d\Psi_L(z_S,0) = d\Psi^{nls}(z_S,0), \quad \forall z_S \in V_S.$$  \hfill (3.6)

Furthermore, $\Psi_L : V \cap h_0^c \to H_0^c$ is a real analytic diffeomorphism onto its image.

(L2) The map $B_L := \Psi_L - F_{nls}^{-1} : V \to H_0^c$ is analytic and one smoothing. More precisely, the analytic map $B_L$ is given by

$$B_L(z) = B^{nls}(\Pi_S z) + d_B^{nls}(\Pi_S z)z_L$$  \hfill (3.7)

with $B^{nls}$ being the map introduced in Theorem 1.1, and for any $s \in \mathbb{Z}_{\geq 1}$, $B_L : V \cap h_0^s \to H_0^{s+1}$ is real analytic. Furthermore

$$d_B B_L(z) = d_B B^{nls}(\Pi_S z), \quad d^2 B_L(z) = 0, \quad \forall z \in V$$

and for any $z \in V \cap h_0^s$, $\alpha, \beta \in \mathbb{Z}_{\geq 0}$,

$$\|\partial^\alpha\beta B_L(z)\|_0 \lesssim_{\alpha, \beta} 1, \quad \|\partial^\alpha\beta d_B B_L(z)\|_0 \lesssim_{\alpha, \beta} \|z\|_0, \quad \forall z \in h_0^{0c}$$  \hfill (3.8)

and for any $s \in \mathbb{Z}_{\geq 1}$, $z \in V \cap h_0^s$,

$$\|\partial^\alpha\beta B_L(z)\|_{s+1} \lesssim_{\alpha, \beta} 1 + \|z\|_s, \quad \|\partial^\alpha\beta d_B B_L(z)\|_{s+1} \lesssim_{\alpha, \beta} \|z\|_s, \quad \forall z \in h_0^{0c}.$$  \hfill (3.9)

(L3) For any $s \in \mathbb{Z}_{\geq 1}$, the restriction $\Psi_L |_{V \cap h_0^s}$ is a map $V \cap h_0^s \to H_0^s$ which is a real analytic diffeomorphism onto its image.

(L4) The map $A_L := \Psi_L^{-1} - F_{nls} : \Psi_L(V) \to h_0^s$ is analytic and one smoothing, meaning that for any $s \in \mathbb{Z}_{\geq 1}$, $A_L : \Psi_L(V) \cap h_0^s \to h_0^{s+1}$ is real analytic.

Remark 3.1. For convenience, in the sequel, we always choose $V_L$ to be a ball of radius smaller than one.

Proof. Choose $V_S$ to be an open bounded neighbourhood of $K$ in $C^S \times C^S$ so that $\nabla_S \subseteq \nabla_S^{\max}$ and $V_L$ an open ball in $h_0^{0c}$, centered at 0, so that item (ii) of Lemma 3.1 applies to $V := V_S \times V_L$, implying that $\Psi_L : V \cap h_0^c \to H_0^c$ is 1-1 and a local diffeomorphism. The identities (3.6) hold by the definition of $\Psi_L$ and the analyticity of $\Psi_L$, stated in (L1), follows by Lemma 3.1(i). One then concludes that

$$\Psi_L : V \cap h_0^c \to H_0^c$$

is a real analytic diffeomorphism onto its image. (L2) follows from the definition of $\Psi_L$, Theorem 1.1, the compactness of $\nabla_S$, and standard estimates in Sobolev spaces. Concerning (L3), first note that by Theorem 1.1 for any $s \in \mathbb{Z}_{\geq 1}$, the restriction $\Psi_L |_{V \cap h_0^s}$ is a map with values in $H_0^s$ and as such real analytic. By item (L1), $\Psi_L |_{V \cap h_0^s}$ is 1-1 and so is its differential $d\Psi_L(z) : h_0^c \to H_0^c$ at any point $z \in V \cap h_0^s$. Since by (L2) the map $B_L$ is one smoothing, $d\Psi_L(z) : h_0^c \to H_0^c$ is Fredholm and hence a linear isomorphism, implying that $\Psi_L : V \cap h_0^s \to H_0^s$ is a real analytic diffeomorphism onto its image. Finally, item (L4) follows from (L3) and Theorem 1.1.

Whereas the tame estimates (3.3) for $B_L$ are an immediate consequence of the definition of $\Psi_L$, Theorem 1.1 and the compactness of $\nabla_S$, this is not so for $A_L$. Actually, for the applications in perturbation theory considered in subsequent work, we only need to derive tame estimates for

$$A_L : V \cap h_0^c \to L(H_0^c, H_0^0), \quad z \mapsto A_L(z) := dA_L(\Psi_L(z)) = d\Psi_L(z)^{-1} - F_{nls}$$  \hfill (3.10)

with $V$ denoting the neighborhood of $K \times \{0\}$ of Proposition 5.1. By formula (3.5), for any $z \in V \cap h_0^c$, the operator $d\Psi_L(z) \in L(h_0^c, H_0^0)$ can be written as

$$d\Psi_L(z) = T(z) + R(z), \quad T(z) := d\Psi^{nls}(\Pi_S z)$$  \hfill (3.11)
with $R(z) \in L(h^0, H^0)$ given by
\[
R(z) : h^0 \to H^0, \quad \hat{z} \mapsto R(z)[\hat{z}] := d^2\Psi^{nls}(\Pi S z)[|\Pi S \hat{z}, \Pi_{\perp} z] = d^2 B^{nls}(\Pi S z)[|\Pi S \hat{z}, \Pi_{\perp} z]. \tag{3.12}
\]
Since by Theorem 1.1 respectively Proposition 3.3 the operators $T(z), d\Psi_L(z) : h^0 \to H^0$ are invertible, so is $T(z)^{-1}d\Psi_L(z) = \Id + T(z)^{-1}R(z)$, implying that
\[
d\Psi_L(z)^{-1} = (\Id + T(z)^{-1}R(z))^{-1}T(z)^{-1} = T(z)^{-1} - T(z)^{-1}R(z)S(z) \tag{3.13}
\]
where
\[
S(z) := (\Id + T(z)^{-1}R(z))^{-1}T(z)^{-1} \in L(H^0, h^0). \tag{3.14}
\]
Furthermore, by Theorem 1.2
\[
T(z)^{-1} = (d\Phi^{nls}(\Pi S z))^{-1} = d\Phi^{nls}(\Pi S z) = F_{nls} + dA^{nls}(\Psi^{nls}(\Pi S z)). \tag{3.15}
\]
Altogether, it follows that for any $z \in V \cap h^0$, the operator $A_L(z) = d\Psi_L(z)^{-1} - F_{nls} : h^0 \to H^0$ can be written as
\[
A_L(z) = dA^{nls}(\Psi^{nls}(\Pi S z)) - T(z)^{-1}R(z)S(z). \tag{3.16}
\]
Finally we note that by (L4) of Proposition 3.3 $A_L = dA_L \circ \Psi_L$ is one smoothing. More precisely, for any $s \in \mathbb{Z}_{>1}$, the restriction of $A_L$ to $V \cap h^s$ is a real analytic map,
\[
A_L : V \cap h^s \to L(H^s, h^{s+1}), \quad z \mapsto A_L(z). \tag{3.17}
\]
**Proposition 3.2** (Tame estimates for $A_L$). After shrinking, if necessary, the radius of the ball $V_{\perp}$ in $V = V_S \times V_{\perp}$ of Proposition 3.3 the map $A_L$ satisfies for any $z \in V \cap h^0$, $\tilde{w} \in h^0$,
\[
\|A_L(z)[\tilde{w}]\|_0 \lesssim \|\tilde{w}\|_0
\]
and for any $k \in \mathbb{Z}_{>1}$, $\hat{z}_1, \ldots, \hat{z}_k \in h^0$,
\[
\|d^k (A_L(z)[\tilde{w}])[\hat{z}_1, \ldots, \hat{z}_k]\|_0 \lesssim k \|\tilde{w}\|_0 \prod_{j=1}^k \|\hat{z}_j\|_0. \tag{3.18}
\]
Furthermore, for any $s \in \mathbb{Z}_{>1}, z \in V \cap h^s$, $\tilde{w} \in H^s$,
\[
\|A_L(z)[\tilde{w}]\|_{s+1} \lesssim \|z\|_{s} \|\tilde{w}\|_0 + \|\tilde{w}\|_s \tag{3.19}
\]
and for any $k \geq 1$, $\hat{z}_1, \ldots, \hat{z}_k \in h^s$,
\[
\|d^k (A_L(z)[\tilde{w}])[\hat{z}_1, \ldots, \hat{z}_k]\|_{s+1} \lesssim_{s,k} (\|z\|_s \|\tilde{w}\|_0 + \|\tilde{w}\|_s) \prod_{j=1}^k \|\hat{z}_j\|_0 + \|\tilde{w}\|_0 \prod_{j=1}^k \|\hat{z}_j\|_s \prod_{\ell \neq j} \|\hat{z}_\ell\|_0. \tag{3.20}
\]
**Proof.** First we prove estimate 3.16. The starting point is formula 3.15 for $A_L(z)$. The two terms $dA^{nls}(\Psi^{nls}(\Pi S z))$ and $T(z)^{-1}R(z)S(z)$ are estimated separately. By Theorem 1.1 $\{\Psi^{nls}(\Pi S z) : z \in V \cap h^0\}$ is a relatively compact subset of $H^s$ for any $s \in \mathbb{Z}_{>0}$, and $A^{nls}, B^{nls}$ are one smoothing maps. It implies that for any $s \in \mathbb{Z}_{>1}$,
\[
\|dA^{nls}(\Psi^{nls}(\Pi S z))[\tilde{w}]\|_{s+1} \lesssim \|\tilde{w}\|_s, \quad \forall z \in V \cap h^0, \quad \forall \tilde{w} \in H^s. \tag{3.17}
\]
Since $\|\Pi S \hat{z}\|_s \lesssim \|\Pi S \hat{z}\|_0$ for any $z \in h^0$, the linear operator $R(z)$, defined in 3.12, satisfies
\[
\|R(z)[\hat{z}]\|_{s+1} \lesssim \|z\|_s \|\Pi S \hat{z}\|_s \|\Pi S \hat{z}\|_0 \quad \forall z \in V \cap h^0, \quad \forall \hat{z} \in h^0. \tag{3.18}
\]
Furthermore, also by Theorem 1.1 one has for any $s \in \mathbb{Z}_{>1}$,
\[
\|T(z)^{-1}[\tilde{w}]\|_s \lesssim \|\tilde{w}\|_s, \quad \forall z \in V \cap h^0, \quad \forall \tilde{w} \in H^s. \tag{3.19}
\]
Combining (3.18)-(3.20), formula (3.15) leads to the estimate
\[ \| A_L(z)\hat{\omega} \|_{s+1} \leq \| dA^{ns}(\Psi^{ns}(\Pi_S z))[\hat{\omega}] \|_{s+1} + \| T(z)^{-1}\mathcal{R}(z)S(z)[\hat{\omega}] \|_{s+1} \lesssim_s \| \hat{\omega} \|_s + \| z \|_s \| \mathcal{S}(z)[\hat{\omega}] \|_0. \]  
(3.21)

It remains to estimate \( \| \mathcal{S}(z)[\hat{\omega}] \|_0 \). Recall that by (3.14), \( \mathcal{S}(z) = (\text{Id} + T(z)^{-1}\mathcal{R}(z))^{-1}T(z)^{-1} \). By Theorem 1.1 there exists \( C_0 > 0 \) so that
\[ \| T(z)^{-1}\mathcal{R}(z)\|_0 \leq C_0 \| z \|_0 \| \mathcal{S}(z) \|_0 \quad \forall z \in \mathcal{V} \cap h^0_r, \quad \forall \hat{z} \in h^0_c. \]  
(3.22)

Shrinking the radius of the ball \( \mathcal{V}_\perp \) in \( h^0_{l,c} \), if necessary, so that \( C_0 \| z \|_0 \leq 1 \) for any \( z \in \mathcal{V}_\perp \), the Neumann series of the operator \( (\text{Id} + T(z)^{-1}\mathcal{R}(z))^{-1} \) absolutely converges in \( \mathcal{L}(h^0_c, h^0_c) \) and the operator norm of \( (\text{Id} + T(z)^{-1}\mathcal{R}(z))^{-1} \) in \( \mathcal{L}(h^0_c, h^0_c) \) is bounded by 2. Hence
\[ \| \mathcal{S}(z)[\hat{\omega}] \|_0 \lesssim_s \| \hat{\omega} \|_0, \quad \forall z \in \mathcal{V} \cap h^0_r, \quad \forall \hat{w} \in h^0_c, \]  
(3.23)

implying together with (3.21) the claimed estimate (3.16).

Finally let us prove the estimate (3.17) for the derivatives of \( A_L(z) \). By formula (3.15) for any \( k, s \in \mathbb{Z}_{\geq 1}, \ z \in \mathcal{V} \cap h^s_r, \ \hat{w} \in h^s_c, \) and \( z_1, \ldots, z_k \in h^s_c, \)
\[ \| d^k (A_L(z)\hat{\omega})[z_1, \ldots, z_k] \|_{s+1} \leq \| d^k (dA^{ns}(\Psi^{ns}(\Pi_S z))[\hat{\omega}])\| \| z_1, \ldots, z_k \|_{s+1} + \| d^k (T(z)^{-1}\mathcal{R}(z)S(z)[\hat{\omega}])\| \| z_1, \ldots, z_k \|_{s+1}. \]  
(3.24)

By Theorem 1.1 one concludes that
\[ \| d^k (dA^{ns}(\Psi_L(\Pi_S z))[\hat{\omega}])\| \| z_1, \ldots, z_k \|_{s+1} \lesssim_{s,k} \| \hat{\omega} \|_s \prod_{j=1}^k \| \hat{z}_j \|_0. \]  
(3.25)

Furthermore
\[ \| d^k (T(z)^{-1}\hat{\omega})\| \| z_1, \ldots, z_k \|_s \lesssim_{s,k} \| \hat{\omega} \|_s \prod_{j=1}^k \| \hat{z}_j \|_0, \]  
(3.26)

and
\[ \| d^k (\mathcal{R}(z)[\hat{\omega}])\| \| z_1, \ldots, z_k \|_{s+1} \lesssim_{s,k} \| z \|_s \| \hat{\omega} \|_s \prod_{j=1}^k \| \hat{z}_j \|_0 + \| \hat{\omega} \|_0 \sum_{j=1}^k \| \hat{z}_j \|_s \prod_{i \neq j} \| \hat{z}_i \|_0, \]  
(3.27)

Combining the estimates (3.26)-(3.28) and using the product rule implies that
\[ \| d^k (T(z)^{-1}\mathcal{R}(z)S(z)[\hat{\omega}])\| \| z_1, \ldots, z_k \|_{s+1} \lesssim_{s,k} \] \[ (\| z \|_s \| \hat{\omega} \|_0 + \| \hat{\omega} \|_s) \prod_{j=1}^k \| \hat{z}_j \|_0 + \| \hat{\omega} \|_0 \sum_{j=1}^k \| \hat{z}_j \|_s \prod_{i \neq j} \| \hat{z}_i \|_0. \]  
(3.29)

The three estimates (3.24), (3.25), (3.29) together yield (3.17).

In the remaining part of this section we describe the pullback \( \Psi^*_L \Lambda \) by \( \Psi_L \) of the standard symplectic form \( \Lambda \) on \( h^0_r \); introduced in (2.3). It turns out that \( \Psi^*_L \Lambda \) is not the symplectic form \( \Lambda_M \) of (2.5), making it necessary to construct the symplectic corrector \( \Psi_C \); see Section 4 below.

Given a bounded linear operator \( \mathcal{P} : h^0_r \to h^0_c \), its transpose \( \mathcal{P}^t : h^0_c \to h^0_c \) is defined to be the operator determined by
\[ (\mathcal{P}[\hat{z}], \hat{z}')_r = (\hat{z}, \mathcal{P}[\hat{z}'])_r, \quad \forall \hat{z}, \hat{z}' \in h^0_c, \]  
(3.30)
where the bilinear form $(\cdot, \cdot)_r$ on $h^0_c$ is defined in (2.4). Similarly, for a bounded linear operator $Q : h^0_c \to H^0_c$, we denote its transpose by $Q^t : H^0_c \to h^0_c$, determined by

$$
\langle Q(z), \hat{w} \rangle_r = \langle \hat{z}, Q^t(\hat{w}) \rangle_r, \quad \forall \hat{z} \in h^0_c, \hat{w} \in H^0_c,
$$

where the bilinear form $(\cdot, \cdot)_r$ on $H^0_c$ is the one introduced in (2.2). We now compute the pullback $\Psi^*_L \Lambda(z)$ at $z = (z_S, z_L) \in h^0_c$ applied to $\hat{z} = (\hat{z}_S, \hat{z}_L)$, $\hat{z}' = (\hat{z}'_S, \hat{z}'_L)$. By the definition of the pullback and the one of $\Lambda$ in (2.3) we have

$$
\Psi^*_L \Lambda(z)[\hat{z}, \hat{z}'] = \Lambda(\Psi_L(z))[d\Psi_L(z)[\hat{z}], d\Psi_L(z)[\hat{z}']] = i \langle d\Psi_L(z)[\hat{z}], d\Psi_L(z)[\hat{z}'] \rangle_r.
$$

By formula (3.3) for $d\Psi_L(z)$,

$$
d\Psi_L(z)[\hat{z}] = d\Psi^{nls}(\Pi_S z)[\hat{z}] + d_S \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S],
$$

one gets

$$
\Psi^*_L \Lambda(z)[\hat{z}, \hat{z}'] = (I) + (II) + (III) + (IV)
$$

where

$$
(I) := i \langle d\Psi^{nls}(\Pi_S z)[\hat{z}], d\Psi^{nls}(\Pi_S z)[\hat{z}'] \rangle_r = \langle (\Psi^{nls})^* \Lambda(\Pi_S z)[\hat{z}], \hat{z}' \rangle_r,
$$

$$
(II) := i \langle d_d \Psi^{nls}(\Pi_S z)[\hat{z}], d_S \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S] \rangle_r.
$$

Writing $d\Psi^{nls}(\Pi_S z)[\hat{z}]$ as $d_S \Psi^{nls}(\Pi_S z)[\hat{z}_S] + d_\bot \Psi^{nls}(\Pi_S z)[\hat{z}_L]$ one gets

$$
(II) = i \langle d_d \Psi^{nls}(\Pi_S z)[\hat{z}], d_S \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S] \rangle_r
+ i \langle d_\bot \Psi^{nls}(\Pi_S z)[\hat{z}_L], d_S \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S] \rangle_r.
$$

Similarly one has

$$
(III) := i \langle d_d \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S], d\Psi^{nls}(\Pi_S z)[\hat{z}_S] \rangle_r
= i \langle d_d \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S], d_S \Psi^{nls}(\Pi_S z)[\hat{z}_S] \rangle_r
+ i \langle d_\bot \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S], d_\bot \Psi^{nls}(\Pi_S z)[\hat{z}_S] \rangle_r.
$$

and finally

$$
(IV) := i \langle d_d \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S], d_S \{ d_\bot \Psi^{nls}(\Pi_S z)[z_L]\} [\hat{z}_S] \rangle_r.
$$

Since by Theorem (3.4) $\Psi^{nls}$ is symplectic, one has $(\Psi^{nls})^* \Lambda = \Lambda_M$. Hence for any $z \in \mathcal{V}$, $\Psi^*_L \Lambda(z)$ can be written as

$$
\Psi^*_L \Lambda(z) = \Lambda_M + \Lambda_L(z), \quad \Lambda_L(z)[\hat{z}, \hat{z}'] := \langle L(z)[\hat{z}], \hat{z}' \rangle_r,
$$

where $L(z) : C^S \times C^S \times h^0_L \to C^S \times C^S \times h^0_L$ is the linear operator of the form

$$
L(z) = \begin{pmatrix} L^S_S(z) & L^S_L(z) \\ L^L_S(z) & 0 \end{pmatrix}.
$$
By the computations above, \( L_\Sigma(z) : C^S \times C^S \to C^S \times C^S \), \( L^\perp_\Sigma(z) : h^{0 \perp}_c \to C^S \times C^S \), and \( L^\perp_\Sigma(z) : C^S \times C^S \to h^{0 \perp}_c \) are the linear operators defined by \( z \in V \cap h^{0 \perp}_c \), \( \tilde{z}_S \in C^S \times C^S \), \( \tilde{z} \perp \in h^{0 \perp}_c \)

\[
L^\perp_\Sigma(z)[\tilde{z}_S] := i \left( \begin{array}{c} (\langle J_{\Sigma}(\Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \\ (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \end{array} \right)
+ i \left( \begin{array}{c} (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \\ (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \end{array} \right)
+ i \left( \begin{array}{c} (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \\ (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \end{array} \right)
(3.41)
\]

and similarly

\[
L^\perp_{\Sigma}(z)[\tilde{z}_S] := i \left( \begin{array}{c} (\langle J_{\Sigma}(\Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \\ (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \end{array} \right)
+ i \left( \begin{array}{c} (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \\ (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \end{array} \right)
(3.42)
\]

\[
L^\perp_{\Sigma}(z)[\tilde{z}_S] := i \left( \begin{array}{c} (\langle J_{\Sigma}(\Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \\ (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \end{array} \right)
+ i \left( \begin{array}{c} (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \\ (\langle J_{\Sigma}(d_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S], \partial_{\tilde{z}_S} \Psi^{nls}_S(z)[\tilde{z}_S]) \rangle_{r} \rangle_{j \in E} \end{array} \right)
(3.43)
\]

The operator valued map \( z \mapsto L(z) \) has the following properties:

**Lemma 3.2.** The map \( L : V \cap h^0 \to L(h^0_c, h^{0 \perp}_c), z \mapsto L(z) \) is real analytic. For any \( z \in V \cap h^0, \tilde{z} \in h^{0 \perp}_c \),

\[
\|L(z)[\tilde{z}]\|_0 \lesssim \|z\|_0 \|\tilde{z}\|_0
\]

and for any \( k \in \mathbb{Z}_{\geq 1}, \tilde{z}_1, \ldots, \tilde{z}_k \in h^{0 \perp}_c \),

\[
\|d^k(L(z)[\tilde{z}])[\tilde{z}_1, \ldots, \tilde{z}_k]\|_0 \lesssim_k \|\tilde{z}\|_0 \prod_{j=1}^k \|	ilde{z}_j\|_0.
\]

Furthermore, the map \( L \) is one smoothing, meaning that for any \( s \in \mathbb{Z}_{\geq 1} \), \( L : V \cap h^s \to L(h^0_c, h^{s+1}) \), \( z \mapsto L(z) \) is real analytic and satisfies the following estimates: for any \( z \in V \cap h^s, \tilde{z} \in h^{s \perp}_c \),

\[
\|L(z)[\tilde{z}]\|_{s+1} \lesssim_s \|z\|_s \|\tilde{z}\|_0
\]

and for any \( k \in \mathbb{Z}_{\geq 1}, z \in V \cap h^s, \tilde{z}_1, \ldots, \tilde{z}_k \in h^{s \perp}_c \),

\[
\|d^k(L(z)[\tilde{z}])[\tilde{z}_1, \ldots, \tilde{z}_k]\|_{s+1} \lesssim_{s,k} \|\tilde{z}\|_0 \prod_{j=1}^k \|	ilde{z}_j\|_0 + \|\tilde{z}\|_s \|z\|_s \prod_{j=1}^k \|	ilde{z}_j\|_0.
\]

In particular, \( L(z) = 0 \) for any \( z \in V \cap h^0 \) with \( z \perp = 0 \). Finally, \( L(z) = -L(z)^t \) or, more explicitly, for any \( z \in V \cap h^0_c \),

\[
L^\perp_\Sigma(z)^t = -L^\perp_\Sigma(z), \quad L^\perp_\Sigma(z)^t = -L^\perp_\Sigma(z), \quad L^\perp_\Sigma(z)^t = -L^\perp_\Sigma(z).
\]

**Proof.** The analyticity of \( L \) follows by Theorem 1.1 using again that \( d_S d_{\tilde{z}} \Psi^{nls} = d_S d_{\tilde{z}} B^{nls} \). Since \( J^t = -J \), one reads off from the expressions (3.41)–(3.43) that (3.40) holds. The estimates (3.44) and (3.45) follow from Theorem 1.1 by differentiating the expressions in the definitions of \( L^\perp_\Sigma(z), L^\perp_\Sigma(z), \) and \( L^\perp_\Sigma(z) \) with respect to \( z \).

14

### 4 The symplectic corrector \( \Psi_C \)

In this section we construct the coordinate transformation \( \Psi_C \) on \( V \cap h^0 \) so that the composition \( \Psi_L \circ \Psi_C \) is symplectic. As mentioned in the introduction, we follow Kuksin’s scheme of proof in [14], which uses
arguments of Moser and Weinstein in the given infinite dimensional setup. The map \( \Psi_C \) will be defined as the time one flow of an appropriately chosen non autonomous vector field. In the sequel, \( \mathcal{V} \) denotes the neighborhood of \( K \times 0 \), given by Proposition 3.1 and Proposition 3.2.

For any \( z \in \mathcal{V} \) define the following two and one forms on \( h^0_\circ \),
\[
\Lambda_0 := \Lambda_M, \quad \Lambda(z) := \Psi^* \Lambda(z) = \Lambda_M + \Lambda_L(z), \quad (4.1)
\]
\[
\lambda_0 := \lambda_M, \quad \lambda(z) := \Psi^* \lambda(z). \quad (4.2)
\]

**Analysis of the two form** \( \Lambda(z) \): Note that \( d\lambda_i = \Lambda_i, i = 0, 1, \) and
\[
\Lambda_1 - \Lambda_0 = \Lambda_L = d(\lambda_1 - \lambda_0). \quad (4.3)
\]
In particular, the two form \( \Lambda_L \) is closed. By (3.40) and Theorem 1.1, the operator \( z \in \mathcal{V} \cap h^0_\circ \) is real analytic and the following tame estimates hold: for any \( z \in \mathcal{V} \cap h^0_\circ \),
\[
\text{For any } \tau \in [0, 1], \text{ define the two form } \Lambda_\tau = \Lambda_\tau(z),
\]
\[
\Lambda_\tau := \tau \Lambda_1 + (1 - \tau)\Lambda_0,
\]
which can be written as
\[
\Lambda_\tau(z)[\vec{z}, \vec{z}'] = (\Lambda_\tau(z)[\vec{z}), \vec{z}'])_r, \quad \Lambda_\tau(z) := J^{-1} + L(z).
\]
It turns out that for any \( \tau \in [0, 1] \) and \( z \in \mathcal{V} \cap h^0_\circ \), the map \( \Lambda_\tau(z) \) is invertible and one smoothing. More precisely, the following holds:

**Lemma 4.1.** After shrinking the ball \( \mathcal{V}_0 \subset h^0_\circ \subset \mathcal{V} = \mathcal{V}_0 \times \mathcal{V}_1 \), if necessary, one has that for any \( s \in \mathbb{Z}_{\geq 0} \), \( z \in \mathcal{V} \cap h^s_\circ \), and \( \tau \in [0, 1] \), the operator \( \Lambda_\tau(z) : h^s_\circ \to h^s_\circ \) is invertible and for any \( k \in \mathbb{Z}_{\geq 1} \), \( z \in \mathcal{V} \cap h^0_\circ \), \( \hat{z}, \hat{z}_1, \ldots, \hat{z}_k \in h^0_\circ \),
\[
\| (\Lambda_\tau(z)^{-1} - J)[\vec{z}] \|_0 \lesssim \| z \|_0 \| \hat{z} \|_0, \quad \| d^k(\Lambda_\tau(z)^{-1}[\vec{z}])[\vec{z}_1, \ldots, \vec{z}_k] \|_0 \lesssim k \| \vec{z} \|_0 \prod_{j=1}^k \| \vec{z}_j \|_0.
\]
Moreover for any \( s \in \mathbb{Z}_{\geq 1} \) and \( \tau \in [0, 1] \), the map
\[
\Lambda_\tau^{-1} - J : \mathcal{V} \cap h^s_\circ \to L(h^s_\circ, h^{s+1}_\circ), \quad z \mapsto \Lambda_\tau(z)^{-1} - J
\]
is real analytic and the following tame estimates hold: for any \( k \in \mathbb{Z}_{\geq 1} \), \( z \in \mathcal{V} \cap h^s_\circ \), \( \hat{z}, \hat{z}_1, \ldots, \hat{z}_k \in h^0_\circ \),
\[
\| (\Lambda_\tau(z)^{-1} - J)[\vec{z}] \|_{s+1} \lesssim \| z \|_s \| \hat{z} \|_0, \quad \| d^k(\Lambda_\tau(z)^{-1}[\vec{z}])[\vec{z}_1, \ldots, \vec{z}_k] \|_{s+1} \lesssim_{s,k} \| \vec{z} \|_0 \sum_{j=1}^k \| \vec{z}_j \| \prod_{i \neq j} \| \vec{z}_i \|_0 + \| \vec{z} \|_0 \| z \|_s \prod_{j=1}^k \| \vec{z}_j \|_0.
\]

**Proof.** For any \( \tau \in [0, 1] \), we write
\[
\Lambda_\tau(z) = J^{-1}(\text{Id} + L_\tau(z)), \quad L_\tau(z) := \tau JL(z).
\]
By (3.30) and Theorem 1.1, the operator \( L_\tau(z) \) satisfies the estimate \( \| L_\tau(z)[\vec{z}] \|_0 \leq C_0 \| z \|_0 \| \vec{z} \|_0 \), for any \( z \in \mathcal{V} \cap h^0_\circ \) and \( \vec{z} \in h^0_\circ \) for some constant \( C_0 > 0 \). By shrinking the ball \( \mathcal{V}_0 \), if necessary, one has that for any \( z \in \mathcal{V}_0 \), \( C_0 \| z \|_0 \leq 1/2 \), implying that the operator \( L_\tau(z) \) is invertible and its inverse \( L_\tau(z)^{-1} \) is given by the Neumann series
\[
L_\tau(z)^{-1} = J + \sum_{n \geq 1} (-1)^n L_\tau(z)^n J. \quad (4.6)
\]
By Lemma 3.2, for any \( s, n \in \mathbb{Z}_{\geq 1} \) and \( \tau \in [0, 1] \), one has
\[
\| L_s (z)^n J [\tilde{z}] \|_{s+1} \leq C(s) \| z \|_s \| L_s (z)^n J [\tilde{z}] \|_0 \leq C(s) C_0 \| z \|_0 \| u \|_{n-1} \| \tilde{z} \|_0
\] (4.7)
for some constant \( C(s) > 0 \). Since \( C_0 \| z \|_0 \leq 1/2 \), one gets
\[
\| (L_s (z)^{-1} - J) [\tilde{z}] \|_{s+1} \lesssim \| z \|_s \| \tilde{z} \|_0.
\]
The estimates for the derivatives \( d^k (L_s (z)^{-1} [\tilde{z}]) \) follow by differentiating the expression (4.6) with respect to \( z \) and applying the estimates for \( d^k (L_s (z) [\tilde{z}]) \) of Lemma 3.2.

Since by (4.3), the two form \( \Lambda_L = \Lambda_1 - \Lambda_0 \) is closed and by Lemma 3.2, for any \( z \in V \cap h_0^c \), \( \Lambda_L (\Pi S z) = 0 \), we can apply Lemma 7.1 in Appendix A. It says that the one form
\[
\lambda_L (z) [\tilde{z}] := \int_0^1 \Lambda_L (z_s, t z_\perp) [0, z_\perp] (\tilde{z}_s, t \tilde{z}_\perp) dt
\] (4.8)
satisfies \( d \lambda_L = \Lambda_L \). By (3.35), (3.40), the one form \( \lambda_L (z) \) can be written as
\[
\lambda_L (z) [\tilde{z}] = \int_0^1 \left( (L(z_s, t z_\perp) (0, z_\perp), (\tilde{z}_s, t \tilde{z}_\perp)) dt = \int_0^1 L_S (z_s, t z_\perp) [z_\perp] \cdot \tilde{z}_s dt.
\]
Moreover, using that by (3.32), \( L_S (z_s, t z_\perp) = t L_S (z_s, z_\perp) \), it turns out that
\[
\lambda_L (z) [\tilde{z}] = \left( E(z), \tilde{z} \right)_r, \quad E(z) := (E_S(z), 0) \in \mathbb{C}^S \times \mathbb{C}^S \times h_0^c
\] (4.9)
where
\[
E_S(z) := \frac{1}{2} L_S (z) [z_\perp] = \frac{1}{2} \left( \left( \left[ \left[ d(\Psi^{nils}(\Pi S z) [z_\perp], \partial_s d \Psi^{nils}(\Pi S z) [z_\perp]) \right]_r \right]_j \right)_{j \in S} \right).
\] (4.10)
One of the features of \( \lambda_L (z) \) is that it is quadratic in \( z_\perp \). In more detail, we have the following

**Lemma 4.2.** For any \( s \in \mathbb{Z}_{\geq 0} \), the map \( E : V \cap h_0^c \to h_0^c \) is real analytic and satisfies the following tame estimates: for any \( z \in V \cap h_0^c \), \( \tilde{z} \in h_0^c \),
\[
\| E(z) \|_s \lesssim \| z \|_0^2, \quad \| d E(z) [\tilde{z}] \|_s \lesssim \| \tilde{z} \|_0 \| \tilde{z} \|_0,
\]
and any \( k \geq 2, \tilde{z}_1, \ldots, \tilde{z}_k \in h_0^c \),
\[
\| d^k E(z) [\tilde{z}_1, \ldots, \tilde{z}_k] \|_s \lesssim s k \prod_{j=1}^k \| \tilde{z}_j \|_0.
\]

**Proof.** The lemma follows by the properties of the map \( \Psi^{nils} \), stated in Theorem 1.1 and the fact that \( E = \Pi S E_r, \| \Pi S z \|_s \lesssim \| z \|_0 \) for any vector \( z \in h_0^c \), and \( V_\perp \subset h_0^c \) is a ball of radius smaller than 1.

**Outline of the construction of \( \Psi_C \):** Following arguments of Moser and Weinstein, our candidate for \( \Psi_C \) is \( \Psi_C^{nil} \) where \( X \equiv X(z, \tau) \in h_0^c \) is a non autonomous vector field with well defined flow \( \Psi_X^{nil, \tau} \), \( 0 \leq \tau \leq 1 \), so that \( (\Psi_X^{nil, \tau})^* \Lambda_1 = \Lambda_0 \). Here \( z \in V \) and the flow is normalized by \( \Psi_X^{nil, \tau} (z) = z \). To see how to choose \( X(z, \tau) \), consider the pullback of the two form \( \Lambda_\tau \) by \( (\Psi_X^{nil, \tau})^* \Lambda_\tau \). Since \( (\Psi_X^{nil, \tau})^* = Id \), one has \( (\Psi_X^{nil, \tau})^* \Lambda_1 = \Lambda_0 \). The desired identity \( (\Psi_X^{nil, \tau})^* \Lambda_\tau \) is independent of \( \tau \), i.e., \( \partial_\tau ((\Psi_X^{nil, \tau})^* \Lambda_\tau) = 0 \). Since \( \partial_\tau \Lambda_\tau = \Lambda_\tau - \Lambda_0 = d \Lambda_L \), it turns out that the latter identity holds if \( \lambda_L + \Lambda_\tau (X(z, \tau), \cdot) = 0 \). When expressed in terms of the bilinear form \( (\cdot, \cdot) \), and taking into account the representation (4.5) of \( \Lambda_\tau \) and (4.9) of \( \lambda_L \), the latter identity reads
\[
(E(z), \tilde{z})_r + (L_\tau(z) [X(z, \tau), \tilde{z}])_r = 0.
\] (4.11)
We choose the vector field \( X(z, \tau) \) so that (4.11) is satisfied.
Vector field $X(z, \tau)$ and its flow: Motivated by (4.11), the non autonomous vector field $X(z, \tau)$ is defined by

$$X(z, \tau) := -\mathcal{L}_\tau(z)^{-1}E(z), \quad z \in \mathcal{V}_\perp \times \mathcal{V}_\perp, \quad \tau \in [0, 1].$$

(4.12)

Lemmas 4.1, 4.2 lead to the following

Lemma 4.3. The vector field $X : (\mathcal{V} \cap h^0_\perp) \times [0, 1] \to h^0_\perp$ is real analytic and one smoothing, meaning that for any $s \in \mathbb{Z}_{\geq 1}$

$$X : (\mathcal{V} \cap h^s_\perp) \times [0, 1] \to h^{s+1}_\perp$$

is real analytic. In addition, the following tame estimates hold: for any $\tau \in [0, 1]$, $z \in \mathcal{V} \cap h^0_\perp$, $\hat{z} \in h^0_\perp$,

$$\|X(z, \tau)\|_0 \lesssim \|z\|_0^2, \quad \|dX(z, \tau)\hat{z}\|_0 \lesssim \|z\|_0\|\hat{z}\|_0$$

(4.13)

and for any $k \geq 2$, $\hat{z}_1, \ldots, \hat{z}_k \in h^0_\perp$,

$$\|d^k X(z, \tau)[\hat{z}_1, \ldots, \hat{z}_k]\|_0 \lesssim_k \prod_{j=1}^k \|\hat{z}_j\|_0.$$

Moreover, for any $s \in \mathbb{Z}_{\geq 1}$, $z \in \mathcal{V} \cap h^s_\perp$, $\hat{z} \in h^s_\perp$,

$$\|X(z, \tau)\|_{s+1} \lesssim_s \|z\|_s\|z\|_0, \quad \|dX(z, \tau)\hat{z}\|_{s+1} \lesssim_s \|z\|_s\|\hat{z}\|_s + \|z\|_s\|\hat{z}\|_0$$

(4.14)

and for any $k \geq 2$, $\hat{z}_1, \ldots, \hat{z}_k \in h^s_\perp$,

$$\|d^k X(z, \tau)[\hat{z}_1, \ldots, \hat{z}_k]\|_{s+1} \lesssim_{s,k} \sum_{j=1}^k \|\hat{z}_j\|_s\prod_{i \neq j} \|\hat{z}_i\|_0 + \|z\|_s\prod_{j=1}^k \|\hat{z}_j\|_0.$$

Proof. The lemma follows from Lemmata 4.1, 4.2 \hfill \Box

We now want to study the flow of the non autonomous differential equation

$$\partial_\tau z = X(z, \tau).$$

(4.15)

Recall that for any $r > 0$, we denote by $\mathcal{V}_\perp(r)$ the ball in $h^0_\perp$ of radius $r$, centered at 0, and for any $\tau_0, \tau \in [0, 1]$ by $\Psi_{X}^{\tau_\perp, \tau}$ the flow map of the differential equation (4.13), satisfying $\Psi_{X}^{\tau_\perp, \tau}(z) = z$. By a standard contraction argument, there exists an open neighborhood $\mathcal{V}_\perp(z) \subseteq \mathcal{V}_\perp$ of $K$ in $\mathbb{C}^n \times \mathbb{C}^n$ and $\delta > 0$ with $\mathcal{V}_\perp(2\delta) \subseteq \mathcal{V}_\perp$ such that for any $\tau, \tau_0 \in [0, 1]$

$$\Psi_{X}^{\tau_\perp, \tau} : \mathcal{V}_\perp \cap h^0_\perp \to \mathcal{V}_\perp \cap h^0_\perp, \quad \mathcal{V}_\delta := \mathcal{V}_\perp \times \mathcal{V}_\perp(\delta), \quad \mathcal{V}_{2\delta} := \mathcal{V}_\perp \times \mathcal{V}_\perp(2\delta)$$

(4.16)

is well defined and real analytic. In the next lemma we state the smoothing estimates for $\Psi_{X}^{\tau_\perp, \tau} - \text{id}$ where $\text{id}$ denotes the identity map on $\mathcal{V}_\perp \cap h^0_\perp$.

Lemma 4.4. By choosing $0 < \delta < 1$ smaller, if necessary, it follows that for any $\tau, \tau_0 \in [0, 1]$, the map $\Psi_{X}^{\tau_\perp, \tau} - \text{id} : \mathcal{V}_\delta \cap h^0_\perp \to h^0_\perp$ is one smoothing, meaning that for any $s \in \mathbb{Z}_{\geq 1}$, the map

$$\Psi_{X}^{\tau_\perp, \tau} - \text{id} : \mathcal{V}_\delta \cap h^s_\perp \to h^{s+1}_\perp$$

is real analytic. Furthermore, the following tame estimates hold: for any $z \in \mathcal{V}_\delta \cap h^0_\perp$, $\hat{z} \in h^0_\perp$,

$$\|\Psi_{X}^{\tau_\perp, \tau}(z) - z\|_0 \lesssim \|z\|_0^2, \quad \|\Psi_{X}^{\tau_\perp, \tau}(z) - \text{id})(\hat{z})\|_0 \lesssim \|z\|_0\|\hat{z}\|_0$$

(4.17)

and for any $k \geq 2$, $\hat{z}_1, \ldots, \hat{z}_k \in h^0_\perp$,

$$\|d^k \Psi_{X}^{\tau_\perp, \tau}(z)[\hat{z}_1, \ldots, \hat{z}_k]\|_0 \lesssim_k \prod_{j=1}^k \|\hat{z}_j\|_0.
whereas for any \( s \in \mathbb{Z}_{\geq 1}, z \in V^\prime_s \cap h^*_s, \hat{z} \in h^*_s, \)
\[
\|\Psi^\tau_{X}^0(z) - z\|_{s+1} \lesssim_s \|z\|_s \|z\|_0, \quad \|(d\Psi^\tau_{X}^0(z) - \text{Id})[\hat{z}]\|_{s+1} \lesssim_s \|z\|_0 \|\hat{z}\|_s + \|z\|_s \|\hat{z}\|_0 \quad (4.18)
\]
and for any \( k \geq 2, \hat{z}_1, \ldots, \hat{z}_k \in h^*_s, \)
\[
\|d^{k}\Psi^\tau_{X}^0(z)[\hat{z}_1, \ldots, \hat{z}_k]\|_{s+1} \lesssim_{s,k} \sum_{j=1}^{k} \|\hat{z}_j\|_s \prod_{i \neq j} \|\hat{z}_i\|_0 + \|z\|_s \|\hat{z}\|_0 \cdot
\]

**Proof.** For any \( \tau_0, \tau \in [0,1] \) and \( z \in V^\prime_s \cap h^*_0, \) the flow \( \Psi^\tau_{X}^0(z) \) satisfies the integral equation
\[
\Psi^\tau_{X}^0(z) = z + \int_{\tau_0}^{\tau} X(\Psi^t_{X}^0(z), t) \, dt \quad (4.19).
\]
In view of the estimate (4.14) of the vector field \( X(z, \tau) \), we first estimate \( \|\Pi_\perp \Psi^\tau_{X}^0(z)\|_s \) for \( z \in V^\prime_s \cap h^*_s \) with \( s \in \mathbb{Z}_{\geq 0} \). Applying the operator \( \Pi_\perp \) to both sides of the identity (4.19), one gets
\[
\|\Pi_\perp \Psi^\tau_{X}^0(z)\|_s = \|z\|_s + \int_{\tau_0}^{\tau} \|\Pi_\perp X(\Psi^t_{X}^0(z), t)\|_s \, dt.
\]
By Lemma 4.3, for any \( \tau, \tau_0 \in [0,1] \), one has
\[
\|\Pi_\perp \Psi^\tau_{X}^0(z)\|_s \leq \|z\|_s + C(s) \int_{\tau_0}^{\tau} \|\Pi_\perp \Psi^t_{X}^0(z)\|_s \|\Pi_\perp \Psi^t_{X}^0(z)\|_0 \, dt \quad (4.20)
\]
for some constant \( C(s) > 0 \), only depending on \( s \). Then by shrinking \( \delta > 0 \), if necessary, so that for \( z \in V_\perp(\delta) \), we have \( \sup_{\tau_0, \tau \in [0,1]} \|\Pi_\perp \Psi^\tau_{X}^0(z)\|_0 \leq 1 \), the above estimate becomes
\[
\|\Pi_\perp \Psi^\tau_{X}^0(z)\|_s \leq \|z\|_s + C(s) \int_{\tau_0}^{\tau} \|\Pi_\perp \Psi^t_{X}^0(z)\|_s \, dt \quad (4.21)
\]
By the Gronwall inequality one then gets
\[
\sup_{\tau_0, \tau \in [0,1]} \|\Pi_\perp \Psi^\tau_{X}^0(z)\|_s \leq \|z\|_s \quad \forall z \in V^\prime_s \cap h^*_s \quad (4.22)
\]
Now let us prove (4.18). By (4.19), using again Lemma 4.3 one gets for any \( s \in \mathbb{Z}_{\geq 1}, \tau_0, \tau \in [0,1] \), and \( z \in V^\prime_s \cap h^*_s \)
\[
\|\Psi^\tau_{X}^0(z) - z\|_{s+1} \lesssim_s \|z\|_s \|z\|_0 \quad (4.23)
\]
which is the first claimed inequality in (4.18). To prove the one for the differential \( d\Psi^\tau_{X}^0 - \text{Id} \), differentiate (4.19) with respect to \( z \). Using the chain rule one gets
\[
d\Psi^\tau_{X}^0(z)[\hat{z}] = \hat{z} + \int_{\tau_0}^{\tau} dX(\Psi^t_{X}^0(z), t)[d\Psi^t_{X}^0(z)[\hat{z}]] \, dt \quad (4.24)
\]
By applying the estimates of \( dX(\cdot, \tau) \) of Lemma 4.3 it follows that for any \( s \in \mathbb{Z}_{\geq 0} \) there is a constant \( C(s) > 0 \) such that
\[
\|d\Psi^\tau_{X}^0(z)[\hat{z}]\|_s \leq \|\hat{z}\|_s + C(s) \int_{\tau_0}^{\tau} \left( \|\Pi_\perp \Psi^t_{X}^0(z)\|_s \|d\Psi^t_{X}^0(z)[\hat{z}]\|_0 + \|\Pi_\perp \Psi^t_{X}^0(z)\|_0 \|d\Psi^t_{X}^0(z)[\hat{z}]\|_s \right) \, dt \quad (4.25)
\]
for some constant $C_1(s) > C(s) > 0$. For $s = 0$, using that $\|z_\perp\|_0 \leq \delta < 1$, (4.25) becomes
$$\|d\Psi_{\tau}^{0, \tau}(z)(\hat{z})\|_0 \leq \|\hat{z}\|_0 + 2C_1(0)\left(\int_{\tau_0}^{\tau} \|d\Psi_{\tau}^{0, \tau}(z)(\hat{z})\|_0 \, dt\right)$$
and hence by the Gronwall inequality
$$\|d\Psi_{\tau}^{0, \tau}(z)(\hat{z})\|_0 \lesssim \|\hat{z}\|_0.$$  
For $s \in \mathbb{Z}_{\geq 1}$, substitute the latter estimate into (4.25) to get, again using that $\|z_\perp\|_0 < \delta < 1$
$$\|d\Psi_{\tau}^{0, \tau}(z)(\hat{z})\|_s \leq \|\hat{z}\|_s + C_2(s)\|z_\perp\|_s \|\hat{z}\|_0 + C_2(s)\left(\int_{\tau_0}^{\tau} \|d\Psi_{\tau}^{0, \tau}(z)(\hat{z})\|_s \, dt\right)$$
for some constant $C_2(s) > C_1(s)$. Then using again the Gronwall inequality one concludes that for any $0 \leq \tau_0 \leq 1$,
$$\sup_{\tau \in [0,1]} \|d\Psi_{\tau}^{0, \tau}(z)(\hat{z})\|_s \lesssim_s \|\hat{z}\|_s + \|z_\perp\|_s \|\hat{z}\|_0.$$  
We are now ready to prove the second estimate in (4.18). By (4.24) and the smoothing estimates on $dX(\cdot, \tau)$ of Lemma 4.3 one gets that for any $s \in \mathbb{Z}_{\geq 1}$, $0 \leq \tau_0 \leq 1$,
$$\|(d\Psi_{\tau}^{0, \tau}(z) - \text{Id})(\hat{z})\|_{s+1} \lesssim_s \sup_{\tau \in [0,1]} \|\Pi_{\perp} \Psi_{\tau}^{0, \tau}(z)\|_s \sup_{\tau \in [0,1]} \|d\Psi_{\tau}^{0, \tau}(z)(\hat{z})\|_0 + \sup_{\tau \in [0,1]} \|\Pi_{\perp} \Psi_{\tau}^{0, \tau}(z)\|_s \sup_{\tau \in [0,1]} \|d\Psi_{\tau}^{0, \tau}(z)(\hat{z})\|_s$$
$$\lesssim_{s+2} \|z_\perp\|_s \|\hat{z}\|_0 + \|z_\perp\|_0 \|\hat{z}\|_s,$$
where we used again that $\|z_\perp\|_0 < \delta < 1$. Hence the claimed estimate for $d\Psi_{\tau}^{0, \tau}(z) - \text{Id}$ in (4.18) is established. The estimates for the higher order derivatives $d^k \Psi_{\tau}^{0, \tau}$, $k \geq 2$, follow by similar arguments, differentiating $k$-times the equation (4.19) with respect to $z$.

**Definition of $\Psi_C$ and its properties:** Our candidate for the symplectic corrector is the time one flow map of $X(z, \tau)$,
$$\Psi_C := \Psi_{\tau}^{0, 1} : \mathcal{V}_{\delta} \cap h_0^0 \to h_r^0.$$  
(4.28)
Clearly, $\Psi_C$ is one to one and its inverse is given by the backward flow of the PDE (4.15), namely $\Psi_{\tau}^{-1} = \Psi_{X}^{1, 0}$. Hence the maps $\Psi_{C, 0}^{\pm}$ satisfy the estimates stated in Lemma 4.2. Furthermore, recall that for any $\tau \in [0,1]$, the two form $\Lambda_\tau$ admits the representation (4.25). Then the following Darboux lemma holds.

**Proposition 4.1.** The map $\Psi_C$ is a symplectic corrector, i.e., for any $z \in \mathcal{V}_{\delta} \cap h_0^0$, $\Psi_{C, 1}(z) = \Lambda_0$.

**Proof.** For any $\tau \in [0,1]$, consider the two form $(\Psi_{\tau}^{0, \tau})^* \Lambda_\tau$. Since $\Psi_{\tau}^{0, 0} = \text{Id}$, one has $(\Psi_{\tau}^{0, \tau})^* \Lambda_0 = \Lambda_0$ and hence it suffices to prove that the map $\tau \mapsto (\Psi_{\tau}^{0, \tau})^* \Lambda_\tau$ is constant or, equivalently,
$$\partial_\tau ((\Psi_{\tau}^{0, \tau})^* \Lambda_\tau) = 0, \quad \forall \tau \in [0,1].$$
By Cartan’s identity (see for instance Lemma 1.2 in [14]) and the fact that $\Lambda_\tau$ is closed, it follows that
$$\partial_\tau ((\Psi_{\tau}^{0, \tau})^* \Lambda_\tau) = (\Psi_{\tau}^{0, \tau})^* (\partial_\tau \Lambda_\tau + d(\Lambda_\tau[X(\cdot, \tau), \cdot])).$$  
Since $\partial_\tau \Lambda_\tau \equiv \Lambda_1 - \Lambda_0 = \Lambda_L$ and $\Lambda_L \equiv d\Lambda_L$, it remains to prove that
$$d(\Lambda_L + \Lambda[X(\cdot, \tau), \cdot]) = 0.$$  
By (4.5), (4.16), (4.12), one has for any $\tau \in [0,1]$, $z \in \mathcal{V}_{\delta} \cap h_0^0$, and $\hat{z} \in h_0^0$
$$\lambda_L(z)(\hat{z}) + \Lambda[X(z, \tau), \hat{z}] = (E(z), \hat{z})_\tau - (\mathcal{L}_\tau(z)\mathcal{L}_\tau(z)^{-1}E(z, \hat{z}))_\tau = 0.$$  
It means that
$$\lambda_L + \Lambda[X(\cdot, \tau), \cdot] = 0, \quad \forall \tau \in [0,1],$$
proving the proposition. 


As a consequence of Lemma 4.4 we get the following

**Corollary 4.1.** (i) For any $s \in \mathbb{Z}_{\geq 0}$, the map $\Psi_C : \mathcal{V}_s^1 \cap h_s^* \to h_s^*$ is a real analytic diffeomorphism onto its image and its nonlinear part is one smoothing, meaning that for any $s \in \mathbb{Z}_{\geq 1}$, the map $B_C := \Psi_C - \mathrm{id} : \mathcal{V}_s^1 \cap h_s^* \to h_{s+1}^* \to h_{s+1}^*$ is real analytic. Furthermore, $B_C$ satisfies the following tame estimates: for any $z \in \mathcal{V}_s^1 \cap h_s^*$, $\delta \in h_{s}^0$,
\[
\|B_C(z)\|_0 \lesssim \|z\|_0^2, \quad \|dB_C(z)[\bar{z}]\|_0 \lesssim \|z\|_0\|\bar{z}\|_0
\]
and for any $k \geq 2$, $\hat{z}_1, \ldots, \hat{z}_k \in h_s^0$,
\[
\|d^k B_C(z)[\hat{z}_1, \ldots, \hat{z}_k]\|_0 \lesssim_k \prod_{j=1}^k \|\hat{z}_j\|_0,
\]
whereas for any $s \in \mathbb{Z}_{\geq 1}$, $z \in \mathcal{V}_s^1 \cap h_s^*$, $\hat{z} \in h_s^0$,
\[
\|B_C(z)\|_{s+1} \lesssim_s \|z\|_s\|\bar{z}\|_0, \quad \|dB_C(z)[\bar{z}]\|_{s+1} \lesssim_s \|z\|_s\|\bar{z}\|_s + \|z\|_s\|\bar{z}\|_0
\]
and for any $k \geq 2$, $\hat{z}, \hat{z}_1, \ldots, \hat{z}_k \in h_s^0$,
\[
\|d^k B_C(z)[\hat{z}, \hat{z}_1, \ldots, \hat{z}_k]\|_{s+1} \lesssim_s k \sum_{j=1}^k \|\hat{z}_j\|_s \prod_{j \neq j'} \|\hat{z}_{j'}\|_0 + \|z\|_s\|\bar{z}\|_s \sum_{j=1}^k \|\hat{z}_j\|_0.
\]
(ii) The map $A_C := \Psi_C^{-1} - \mathrm{id} : \Psi_C(\mathcal{V}_s^1) \cap h_s^0 \to h_s^0$ is real analytic and satisfies the following tame estimates: for any $z \in \Psi_C(\mathcal{V}_s^1) \cap h_s^0$, $\hat{z} \in h_s^0$,
\[
\|A_C(z)\|_0 \lesssim \|z\|_0^2, \quad \|dA_C(z)[\bar{z}]\|_0 \lesssim \|z\|_0\|\bar{z}\|_0
\]
and for any $k \geq 2$, $\hat{z}_1, \ldots, \hat{z}_k \in h_s^0$,
\[
\|d^k A_C(z)[\hat{z}_1, \ldots, \hat{z}_k]\|_0 \lesssim_k \prod_{j=1}^k \|\hat{z}_j\|_0.
\]
Furthermore, for any $s \in \mathbb{Z}_{\geq 1}$, $A_C : \Psi_C(\mathcal{V}_s^1) \cap h_s^* \to h_{s+1}^*$ is real analytic and satisfies the following tame estimates: for any $z \in \Psi_C(\mathcal{V}_s^1) \cap h_s^*$, $\hat{z} \in h_s^*$,
\[
\|A_C(z)\|_{s+1} \lesssim_s \|z\|_s\|\bar{z}\|_0, \quad \|dA_C(z)[\bar{z}]\|_{s+1} \lesssim_s \|z\|_s\|\bar{z}\|_s + \|z\|_s\|\bar{z}\|_0
\]
and for any $k \geq 2$, $\hat{z}_1, \ldots, \hat{z}_k \in h_s^*$,
\[
\|d^k A_C(z)[\hat{z}_1, \ldots, \hat{z}_k]\|_{s+1} \lesssim_s k \sum_{j=1}^k \|\hat{z}_j\|_s \prod_{j \neq j'} \|\hat{z}_{j'}\|_0 + \|z\|_s\|\bar{z}\|_s \sum_{j=1}^k \|\hat{z}_j\|_0.
\]

**Proof.** The claimed results are a special case of Lemma 4.4 since $\Psi_C = \Psi_X^{0,1}$ and $\Psi_C^{-1} = \Psi_X^{1,0}$. $\Box$

An immediate consequence of Corollary 4.1 is the following result, needed in Subsection 5.2.

**Corollary 4.2.** The Taylor expansion of the map $B_C = \Psi_C - \mathrm{id}$ around $\Pi S \bar{z}$ up to order three is of the form
\[
B_C(z) = B_{2}^C(z) + B_{3}^C(z), \quad z \in \mathcal{V}_s^1 \cap h_s^0,
\]
where
\[
B_{2}^C(z) := \frac{1}{2} d^2 B_C(\Pi S \bar{z})[\Pi_{\perp} \bar{z}, \Pi_{\perp} \bar{z}]
\]  
and $B_{3}^C(z)$ is the Taylor remainder term
\[
B_{3}^C(z) := \frac{1}{2} \int_0^1 (1 - t)^2 d^3 B_C(\Pi S \bar{z} + t\Pi_{\perp} \bar{z})[\Pi_{\perp} \bar{z}, \Pi_{\perp} \bar{z}, \Pi_{\perp} \bar{z}] \, dt.
\]
The maps \( B^C_i : \mathcal{V}^c_i \cap h^r_i \to h^r_i, \quad i = 2, 3, \) are real analytic and \( B^C_i \) satisfies the following estimates: for any \( z \in \mathcal{V}^c_i \cap h^r_i, \hat{z}, \hat{z}_1, \hat{z}_2 \in h^c_c,
\begin{align*}
\| B^C_i(z) \|_0 \lesssim \| z \|_0^3, \quad \| d B^C_i(z) \| \lesssim \| z \|_0^2 \| \hat{z} \|_0, \quad \| d^2 B^C_i(z) \| \lesssim \| z \|_0 \| \hat{z}_1 \|_0 \| \hat{z}_2 \|_0
\end{align*}
and for any \( k \geq 3, \hat{z}_1, \ldots, \hat{z}_k \in h^c_c,
\begin{align*}
\| d^k B^C_i(z) \| \lesssim_k \prod_{j=1}^k \| \hat{z}_j \|_0.
\end{align*}
Furthermore, for any \( s \in \mathbb{Z} \geq 1, \ B^C_i : \mathcal{V}^c_i \cap h^r_s \to h^r_{s+1}, \quad i = 2, 3, \) are real analytic and \( B^C_i \) satisfies the following tame estimates: for any \( z \in \mathcal{V}^c_i \cap h^r_s, \hat{z}, \hat{z}_1, \hat{z}_2 \in h^c_c,
\begin{align*}
\| B^C_i(z) \|_{s+1} \lesssim_s \| z \|_s \| \hat{z} \|_0^2, \quad \| d B^C_i(z) \|_{s+1} \lesssim_s \| z \|_s \| \hat{z} \|_0^3 + \| z \|_s \| \hat{z}_1 \|_0 \| \hat{z}_2 \|_0,
\end{align*}
\begin{align*}
\| d^2 B^C_i(z) \|_{s+1} \lesssim_s \| z \|_s \| \hat{z}_1 \|_0 \| \hat{z}_2 \|_0 + \| z \|_s \| \hat{z}_1 \|_0 \| \hat{z}_2 \|_0
\end{align*}
and for any \( k \geq 3, \hat{z}, \hat{z}_1, \ldots, \hat{z}_k \in h^c_c,
\begin{align*}
\| d^k B^C_i(z) \| \lesssim_{s,k} \sum_{j=1}^k \| \hat{z}_j \|_0 \prod_{i \neq j} \| \hat{z}_i \|_0 + \| z \|_s \| \prod_{j=1}^k \| \hat{z}_j \|_0.
\end{align*}

Proof. Note that by Corollary 4.1, \( B_C(\Pi_S z) = 0 \) and \( d B_C(\Pi_S z) = 0. \) Thus \( B_C(z) = B^C(z) + B^C_i(z) \) is the Taylor expansion of \( B_C \) around \( \Pi_S z \) with Taylor remainder term given by (4.30). The claimed analyticity and tame estimates follow from Corollary 4.1. \( \square \)

5 Proof of Theorem 1.2

In this section we prove Theorem 1.2. First we introduce and discuss our new canonical coordinates and then express the Hamiltonian of the defocusing NLS equation in the new coordinates.

5.1 New canonical coordinates

Our candidate of the canonical transformation is the map
\( \Psi := \Psi_0 \circ \Psi_C : \mathcal{V}^c_0 \to \mathcal{H} \)
(5.1)
where \( \mathcal{V}^c_0 \) is the neighborhood introduced in (4.10).

Proposition 5.1. By shrinking \( 0 < \delta < 1, \) if necessary, it follows that for any \( s \in \mathbb{Z} \geq 0, \) \( \Psi : \mathcal{V}^c_0 \cap h^r_s \to h^r_s \) is a real analytic symplectic diffeomorphism onto its image with the property that its nonlinear part \( B := \Psi - F^{-1}_{\text{nl}} : \mathcal{V}^c_0 \cap h^r_0 \to h^r_0 \) satisfies the following estimates: for any \( k \in \mathbb{Z} \geq 1, \ z \in \mathcal{V}^c_0 \cap h^r_s, \hat{z}, \ldots, \hat{z}_k \in h^c_c,
\begin{align*}
\| B(z) \|_0 \lesssim 1, \quad \| d B(z) [\hat{z}_1, \ldots, \hat{z}_k] \|_0 \lesssim_k \prod_{j=1}^k \| \hat{z}_j \|_0.
\end{align*}
Furthermore, \( B \) is one smoothing, meaning that for any \( s \in \mathbb{Z} \geq 2, \) the map \( B : \mathcal{V}^c_0 \cap h^r_s \to h^r_{s+1} \) is real analytic, and it satisfies the following tame estimates: for any \( k \in \mathbb{Z} \geq 1, \ z \in \mathcal{V}^c_0 \cap h^r_s, \hat{z}, \ldots, \hat{z}_k \in h^c_c,
\begin{align*}
\| B(z) \|_{s+1} \lesssim_s 1 + \| z \|_s, \quad \| d B(z) [\hat{z}_1, \ldots, \hat{z}_k] \|_{s+1} \lesssim_{s,k} \sum_{j=1}^k \| \hat{z}_j \|_0 \prod_{i \neq j} \| \hat{z}_i \|_0 + \| z \|_s \| \hat{z}_1 \|_0 \| \hat{z}_2 \|_0 \| \hat{z}_k \|_0.
\end{align*}
Proof. By Proposition 5.1 and Corollary 4.1 one has that for any \( s \in \mathbb{Z}_{\geq 0} \), the map \( \Psi = \Psi_L \circ \Psi_C : V'_s \cap h^*_r \to H'_c \) is real analytic and

\[
\Psi^* \Lambda = (\Psi_L \circ \Psi_C)^* \Lambda = \Psi_C^* \Psi_L^* \Lambda = \Psi_C^* \Lambda_1 = \Lambda_0 = \Lambda_M ,
\]

implying that \( \Psi \) is symplectic. Recalling that \( \Psi_L = F_{\text{nls}}^{-1} + B_L \) (see (3.7)) and using that, by Corollary 4.1, \( \Psi_C = id + B_C \), a direct calculation shows that for any \( z \in V'_s \cap h^*_r \)

\[
B(z) = \Psi(z) - F_{\text{nls}}^{-1}(z) = F_{\text{nls}}^{-1}(B_C(z)) + B_L(\Psi_C(z))
\]

The claimed estimates for \( B \) then follow from the estimates of Proposition 3.1 and the ones of Corollary 4.1.

Substituting formula (3.7) for \( B_L \) one gets

\[
\Psi(z) = F_{\text{nls}}^{-1}(z) + F_{\text{nls}}^{-1}(B_C(z)) + B_{\text{nls}}^n(\Pi_S z + \Pi_S B_C(z)) + d_{\perp} B_{\text{nls}}^n(\Pi_S z + \Pi_S B_C(z))[z_{\perp} + \pi_{\perp} B_C(z)]
\]

where according to Corollary 4.2

\[
B_C(z) = \frac{1}{2} d^2 B_C(\Pi_S z)[\Pi_{z_{\perp}}, \Pi_{z_{\perp}}] + \frac{1}{2} \int_0^1 (1 - t)^2 d^3 B_C(\Pi_S z + t \Pi_S z)[\Pi_{z_{\perp}}, \Pi_{z_{\perp}}, \Pi_{z_{\perp}}] dt .
\]

Next, we state and prove the one smoothing property and tame estimates for the map

\[
A(z) := d\Psi(z)^{-1} - F_{\text{nls}} , \quad z \in V'_s \cap h_r^0 .
\]

By the chain rule,

\[
d\Psi(z)^{-1} = d\Psi_C(z)^{-1} (d\Psi_L(\Psi_C(z)))^{-1} .
\]

Note that by Corollary 4.1

\[
d\Psi_C(z)^{-1} = d\Psi_C^{-1}(\Psi_C(z)) = Id + dA_C(\Psi_C(z)) ,
\]

and that by (3.10), \( d\Psi_L(z)^{-1} = F_{\text{nls}} + A_L(z) \). Hence (5.9) can be written as

\[
d\Psi(z)^{-1} = F_{\text{nls}} + A(z) , \quad A(z) := A_L(\Psi_C(z)) + dA_C(\Psi_C(z))d\Psi_L(\Psi_C(z))^{-1} .
\]

Proposition 5.2 (Tame estimates for \( A \)). For any \( s \in \mathbb{Z}_{\geq 1} \), the map \( A : V'_s \cap h^*_r \to L(H^s_c, h^s_{c+1}) \) is real analytic and satisfies the following tame estimates: for any \( z \in V'_s \cap h^*_r , \hat{w} \in H^0_c \),

\[
\| A(z)[\hat{w}] \|_0 \lesssim \| \hat{w} \|_0
\]

and for any \( k \geq 1 , \hat{z}_1 , \ldots , \hat{z}_k \in h^*_s \),

\[
\| d^k (A(z)[\hat{w}])[\hat{z}_1 , \ldots , \hat{z}_k] \|_0 \lesssim_k \| \hat{w} \|_0 \prod_{j=1}^k \| \hat{z}_j \|_0 .
\]

Moreover, for any \( s \in \mathbb{Z}_{\geq 1} , z \in V'_s \cap h^*_r , w \in H^s_c \),

\[
\| A(z)[\hat{w}] \|_{s+1} \lesssim_s \| z \|_s \| \hat{w} \|_0 + \| \hat{w} \|_{s}
\]

and for any \( k \geq 1 , \hat{z}_1 , \ldots , \hat{z}_k \in h^*_s \),

\[
\| d^k (A(z)[\hat{w}])[\hat{z}_1 , \ldots , \hat{z}_k] \|_{s+1} \lesssim_{s,k} \left( \| z \|_s \| \hat{w} \|_0 + \| \hat{w} \|_{s} \right) \prod_{j=1}^k \| \hat{z}_j \|_0 + \| \hat{w} \|_0 \sum_{j=1}^k \| \hat{z}_j \|_s \prod_{i \neq j} \| \hat{z}_i \|_0 .
\]

Proof. The claimed estimates for \( A \) follow by Lemma 3.2 and Corollary 4.1 by the chain and product rules.

\[22\]
5.2 The defocusing NLS Hamiltonian in new coordinates

In this subsection we prove the expansion of $\mathcal{H}^{nls}_2 \circ \Psi$, stated in (C3) of Theorem 1.2. Recall from 1.2 that the Hamiltonian of the defocusing NLS equation is given by

$$\mathcal{H}^{nls}(w) = \int_0^1 (\partial_x u \partial_t v + u^2 v^2) dx, \quad w = (u, v) \in H^1_t.$$

By Theorem 1.1, $H^{nls} := \mathcal{H}^{nls} \circ \Psi^{nls}$ only depends on the actions. By a slight abuse of notation we write

$$H^{nls} = H^{nls}(I), \quad I = (I_k)_{k \in \mathbb{Z}} \in \ell^1_{+}, \quad I_k \equiv I_k(z) = |z_k|^2/2 = (x_k^2 + y_k^2)/2 \quad \forall k \in \mathbb{Z} \quad (5.8)$$

and denote by $\omega^{nls}_k(I)$ the dNLS frequencies,

$$\omega^{nls}_k(I) := \partial_{I_k} H^{nls}(I), \quad k \in \mathbb{Z}. \quad (5.9)$$

The properties of the frequency map $I \mapsto \omega(I) := (\omega_k(I))_{k \in \mathbb{Z}}$, needed in the sequel, are summarized in the following

**Proposition 5.3. (dNLS frequencies)** The map

$$\ell^1_{+} \to \ell^\infty, \quad (I_k)_{k \in \mathbb{Z}} \mapsto (\omega^{nls}_n(I) - 4\pi^2 n^2)_{n \in \mathbb{Z}} \quad (5.10)$$

is real analytic and bounded.

**Proof.** See e.g. Theorem 3.2 in [2].

With the notation introduced above, the $L^2$-gradient $\nabla H^{nls}(z)$ is then given by

$$\nabla H^{nls}(z) = \Omega^{nls}(I)[z], \quad z \in h^1_t, \quad I \equiv I(z) = (I_n(z))_{n \in \mathbb{Z}}$$

where for any $I \in \ell^1_{+}$, $\Omega^{nls}(I) : h^1_t \to h^{-1}_t$ is the diagonal operator

$$\Omega^{nls}(I) := \begin{pmatrix} \text{diag}_{k \in \mathbb{Z}} \omega^{nls}_k(I) & 0 \\ 0 & \text{diag}_{k \in \mathbb{Z}} \omega^{nls}_k(I) \end{pmatrix}. \quad (5.11)$$

Further note that since $H^{nls}(z) = \mathcal{H}^{nls}(\Psi^{nls}(z))$ one has by the chain rule

$$\Omega^{nls}(I)[z] = \nabla H^{nls}(z) = (d\Psi^{nls}(z))^t \nabla \mathcal{H}^{nls}(\Psi^{nls}(z)), \quad \forall z \in \mathcal{V} \cap h^1_t \quad (5.12)$$

where $\mathcal{V}$ is the neighborhood of $h^0_t$ in $h^0_t$ of Theorem 1.1, $\mathcal{V} = \Phi^{nls}(W)$. For later use we record that (5.12), evaluated at $z$ with $z = \Pi_S z$, reads

$$\Omega^{nls}(I, 0)\Pi_S z = (d\Psi^{nls}(\Pi_S z))^t \nabla \mathcal{H}^{nls}(\Psi^{nls}(\Pi_S z))$$

implying that

$$\Pi_\perp (d\Psi^{nls}(\Pi_S z))^t \nabla \mathcal{H}^{nls}(\Psi^{nls}(\Pi_S z)) = 0. \quad (5.13)$$

The equations of motion, associated to the Hamiltonian $H^{nls}$ are given by

$$\partial_t z = J \Omega^{nls}(I)[z], \quad J = \begin{pmatrix} 0 & -\text{Id} \\ \text{Id} & 0 \end{pmatrix}. \quad (5.14)$$

According to the splitting $z = (z_S, z_\perp) \in \mathbb{C}^S \times \mathbb{C}^S \times h^0_{\perp, t}$, we can decompose the equation (5.14) as

$$\begin{cases} \partial_t z_S = J \Omega^S_{nls}(I)[z_S] \\ \partial_t z_\perp = J \Omega^\perp_{nls}(I)[z_\perp] \end{cases} \quad (5.15)$$
Since $\Psi$, the latter identity implies that for any $t$ and hence (5.24) reads
\[
\Omega S^{nls}(I) := \left( \begin{array}{cc}
\text{diag}_{k \in S} \omega_{k}^{nls}(I) & 0 \\
0 & \text{diag}_{k \in S} \omega_{k}^{nls}(I)
\end{array} \right), \quad \Omega I^{nls}(I) := \left( \begin{array}{cc}
\text{diag}_{k \in S} \omega_{k}^{nls}(I) & 0 \\
0 & \text{diag}_{k \in S} \omega_{k}^{nls}(I)
\end{array} \right).
\]

Similarly, by a slight abuse of terminology, we identify $I = (I_k)_{k \in \mathbb{Z}}$ with $(I_S, I_\perp)$,
\[
I = (I_S, I_\perp), \quad I_S := (I_k)_{k \in S}, \quad I_\perp := (I_k)_{k \in S^\perp}.
\]

Note that although the frequencies $\omega(I)$ are functions of all the action variables $I_n$, $n \in \mathbb{Z}$, the system decouples since the action variables are invariant in time and depend only on the initial data. Now let us assume that $z(t) = (z_S(t), 0)$ is a solution of (5.15) with initial data $z(0) = (z_S^{(0)}, 0)$ and consider the equation obtained from (5.15) by linearizing it along $(z_S(t), 0)$ with initial data given by $\tilde{z}(0) = (0, \tilde{z}_\perp^{(0)})$ and $\tilde{z}_\perp^{(0)} \in h_1^\perp$, and denote by $\tilde{z}(t)$ the corresponding solution which evolves in $h_1^\perp$. By a straightforward computation one verifies that the differential of $\Omega^{nls}(I)$ at $(z_S^{(0)}, 0)$ in direction $(0, \tilde{z}_\perp^{(0)})$ vanishes, implying that $\tilde{z}(t) = (0, \tilde{z}_\perp(t))$ where $\tilde{z}_\perp(t)$ is the solution of
\[
\partial_t \tilde{z}_\perp(t) = J \Omega I^{nls}(I_S, 0)[\tilde{z}_\perp(t)], \quad \tilde{z}_\perp(0) = \tilde{z}_\perp^{(0)}.
\]

Since Theorem 1 shows $h_1 \rightarrow H^1$ is symplectic it follows that
\[
\tilde{w}(t) := d\Psi^{nls}(z_S(t), 0)[(0, \tilde{z}_\perp(t))] = d\Psi^{nls}(z_S(t), 0)[\tilde{z}_\perp(t)]
\]
is a solution of the equation obtained by linearizing the dNLS equation along $\Psi^{nls}(z_S(t), 0)$. More precisely,
\[
\partial_t \tilde{w}(t) = i \tilde{d} \nabla H^{nls}(\Psi^{nls}(z_S(t), 0))[\tilde{w}(t)], \quad \tilde{w}(0) = d\Psi^{nls}(z_S^{(0)}, 0)[(0, \tilde{z}_\perp^{(0)})].
\]

On the other hand, by differentiating formula (5.19) with respect to $t$, one gets
\[
\partial_t \tilde{w}(t) = d_\perp \Psi^{nls}(z_S(t), 0)[\partial_t \tilde{z}_\perp(t)] + d_S(d_\perp \Psi^{nls}(z_S(t), 0)[\tilde{z}_\perp(t)])[\partial_t z_S(t)]
\]
\[
= d_\perp \Psi^{nls}(z_S(t), 0)[J \Omega I^{nls}(I_S, 0)[\tilde{z}_\perp(t)]] + d_S(d_\perp \Psi^{nls}(z_S(t), 0)[\tilde{z}_\perp(t)][J \Omega I^{nls}(I_S, 0)][z_S(t)]).
\]

Comparing (5.20) and (5.21) one gets
\[
i \tilde{d} \nabla H^{nls}(\Psi^{nls}(z_S(t), 0)) \tilde{z}_\perp = d_\perp \Psi^{nls}(z_S(t), 0)[J \Omega I^{nls}(I_S, 0)[\tilde{z}_\perp(t)]
\]
\[
+ d_S(d_\perp \Psi^{nls}(z_S(t), 0)[\tilde{z}_\perp(t)][J \Omega I^{nls}(I_S, 0)][z_S(t)].
\]

The latter identity implies that for any $z_S \in \mathbb{R}^S \times \mathbb{R}^S$, $\tilde{z}_\perp \in h_1^\perp$, \[\]
\[
i \tilde{d} \nabla H^{nls}(\Psi^{nls}(z_S, 0))[0, \tilde{z}_\perp)] = d_\perp \Psi^{nls}(z_S, 0) J \Omega^{nls}(I_S, 0)[0, \tilde{z}_\perp]
\]
\[
+ d_S(d_\perp \Psi^{nls}(z_S, 0)[\tilde{z}_\perp)][J \Omega I^{nls}(I_S, 0)[z_S]).
\]

Solving for $J \Omega I^{nls}(I_S, 0)[0, \tilde{z}_\perp)$, one gets
\[
J \Omega^{nls}(I_S, 0)[0, \tilde{z}_\perp) = (d_\perp \Psi^{nls}(z_S, 0))^{-1}i \tilde{d} \nabla H^{nls}(\Psi^{nls}(z_S, 0)) \tilde{z}_\perp
\]
\[
\quad - (d_\perp \Psi^{nls}(z_S, 0))^{-1}d_S(d_\perp \Psi^{nls}(z_S, 0)[\tilde{z}_\perp)]J \Omega I^{nls}(I_S, 0)[z_S].
\]

Since $\Psi^{nls}$ is symplectic, one has
\[
(d_\perp \Psi^{nls}(z_S, 0))^{-1}i \tilde{d} = J(d_\perp \Psi^{nls}(z_S, 0))i \tilde{d}, \quad (d_\perp \Psi^{nls}(z_S, 0))^{-1} = J(d_\perp \Psi^{nls}(z_S, 0))i \tilde{d}
\]
and hence (5.22) reads
\[
\Omega I^{nls}(I_S, 0)[0, \tilde{z}_\perp) = (d_\perp \Psi^{nls}(z_S, 0))i \tilde{d} \nabla H^{nls}(\Psi^{nls}(z_S, 0))d_\perp \Psi^{nls}(z_S, 0)[0, \tilde{z}_\perp) - R^{(1)}(z_S)[\tilde{z}_\perp]
\]
\[
\quad - (d_\perp \Psi^{nls}(z_S, 0))^{-1}d_S(d_\perp \Psi^{nls}(z_S, 0)[\tilde{z}_\perp)]J \Omega I^{nls}(I_S, 0)[z_S].
\]

where $R^{(1)}(z_S) : h_1^\perp \rightarrow h_0^\perp$ is the bounded linear operator, defined by
\[
R^{(1)}(z_S)[\tilde{z}_\perp) := d_\perp \Psi^{nls}(z_S, 0)i \tilde{d} d_S(d_\perp \Psi^{nls}(z_S, 0)[\tilde{z}_\perp)]J \Omega I^{nls}(I_S, 0)[z_S].
\]

For later use we record the following estimates for $R^{(1)}(z_S)$.
Lemma 5.1. The map $V_S \cap (\mathbb{R}^S \times \mathbb{R}^S) \to \mathcal{L}(h_{x,c}^0, h_{c}^0), z_S \mapsto \mathcal{R}(1)(z_S)$ is real analytic and bounded. Moreover it is one smoothing, meaning that for any $s \in \mathbb{Z}_{\geq 1}$, $V_S \cap (\mathbb{R}^S \times \mathbb{R}^S) \to \mathcal{L}(h_{x,c}^s, h_{c}^s), z_S \mapsto \mathcal{R}(1)(z_S)$ is real analytic. Furthermore, for any $s \in \mathbb{Z}_{\geq 1}$, $z_S \in V_S \cap (\mathbb{R}^S \times \mathbb{R}^S)$,

$$\|\partial_S^{\alpha,\beta} \mathcal{R}(1)(z_S)\|_{\mathcal{L}(h_{x,c}^0, h_{c}^0)} \lesssim_{s, \alpha, \beta} 1, \quad \|\partial_S^{\alpha,\beta} \mathcal{R}(1)(z_S)\|_{\mathcal{L}(h_{x,c}^s, h_{c}^{s+1})} \lesssim_{s, \alpha, \beta} 1.$$ 

Proof. By Theorem 5.1, $\Psi^{nls} = F_{nls}^{-1} + B^{nls}$ and hence $d_S(d_\perp \Psi^{nls}(z_S,0) [\zeta_\perp]) = d_S(d_\perp B^{nls}(z_S,0) [\zeta_\perp])$. The claimed statements then follow from Theorem 5.1.

We also need to record some properties of the operator $\Omega^{nls}_I(I)$ for $I = (I_S,0)$. Write

$$\Omega^{nls}_I(I_S,0) = D^2_\perp + \Omega^{(0)}_I(I_S,0),$$

(5.27)

where

$$D_\perp := \begin{pmatrix} \operatorname{diag}_{\alpha \in S^\perp} (2\pi n) & 0 \\ 0 & \operatorname{diag}_{\alpha \in S^\perp} (2\pi n) \end{pmatrix},$$

(5.28)

and

$$\Omega^{(0)}_I(I_S,0) := \begin{pmatrix} \operatorname{diag}_{\alpha \in S^\perp} (\omega^{nls}_n(I_S,0) - 4\pi^2 n^2) & 0 \\ 0 & \operatorname{diag}_{\alpha \in S^\perp} (\omega^{nls}_n(I_S,0) - 4\pi^2 n^2) \end{pmatrix}. \quad (5.29)$$

Lemma 5.2. For any $s \in \mathbb{Z}_{\geq 0}$, the map $V_S \cap (\mathbb{R}^S \times \mathbb{R}^S) \to \mathcal{L}(h_{x,c}^s, h_{c}^s), z_S \mapsto \Omega^{(0)}_I(I_S(z_S),0)$ is real analytic and bounded.

Proof. The lemma is a straightforward application of Proposition 5.3 since for any $\alpha, \beta \in \mathbb{Z}_{\geq 0}$

$$\sup_{n \in S^\perp} \|\partial_S^{\alpha,\beta} (\omega^{nls}_n(I_S,0) - 4\pi^2 n^2)\| \lesssim_{s, \alpha, \beta} 1$$

and

$$\|\partial_S^{\alpha,\beta} \Omega^{(0)}_I(I_S,0)\|_{\mathcal{L}(h_{x,c}^s, h_{c}^s)} \lesssim_{s, \alpha, \beta} \sup_{n \in S^\perp} \|\partial_S^{\alpha,\beta} (\omega^{nls}_n(I_S,0) - 4\pi^2 n^2)\| \lesssim_{s, \alpha, \beta} 1$$

uniformly on $V_S \cap (\mathbb{R}^S \times \mathbb{R}^S)$. \hfill \Box

After this preliminary discussion, we can now study the transformed Hamiltonian $\mathcal{H}^{nls} \circ \Psi$ where $\Psi = \Psi_L \circ \Psi_C$ is the symplectic transformation introduced in Subsection 6.1. We split the analysis into two parts. First we expand $\mathcal{H}^{(1)} := \mathcal{H}^{nls} \circ \Psi_L$ and then we analyze $\mathcal{H}^{(2)} = \mathcal{H}^{(1)} \circ \Psi_C$.

Expansion of $\mathcal{H}^{nls} \circ \Psi_L$

To expand $\mathcal{H}^{nls} \circ \Psi_L$, it is useful to write $\mathcal{H}^{nls}$ in the form

$$\mathcal{H}^{nls}(w) = \mathcal{H}^{nls}_2(w) + \mathcal{H}^{nls}_4(w) \quad (5.30)$$

where

$$\mathcal{H}^{nls}_2(w) := \frac{1}{2} \langle \mathcal{D}_2 w, w \rangle_r, \quad \mathcal{H}^{nls}_4(w) := \int_{\mathbb{T}} u^2 v^2 \, dx, \quad (5.31)$$

and the operator $\mathcal{D}_2$ is defined as

$$\mathcal{D}_2 := \begin{pmatrix} 0 & -\partial_v \\ -\partial_u & 0 \end{pmatrix}. \quad (5.32)$$

Note that $\mathcal{D}_2 = \mathcal{D}_2^\perp$. The Hamiltonian equations associated to $\mathcal{H}^{nls}$ can be written as

$$\partial_t w = i \mathcal{J} \nabla \mathcal{H}^{nls}(w), \quad \mathcal{J} = \begin{pmatrix} 0 & -\mathcal{I} \\ \mathcal{I} & 0 \end{pmatrix}, \quad \nabla \mathcal{H}^{nls} = (\nabla_u \mathcal{H}^{nls}, \nabla_v \mathcal{H}^{nls}) \quad (5.32)$$

25
where
\[ \nabla H^{\text{nl}}(w) = D_2 w + \nabla H^{\text{nl}}(w), \quad d\nabla H^{\text{nl}}(w) = D_2 + d\nabla H^{\text{nl}}(w). \] (5.33)

The Taylor expansion of \( H^{\text{nl}} \) around \( \Psi^{\text{nl}}(\Pi S z) \) up to order three reads
\[
H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z) + w) = H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z)) + (\nabla H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z)), w)_r + \frac{1}{2} (d\nabla H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z))[w], w)_r \\
+ T_3^{(1)}(z_s, w) 
\] (5.34)

where \( T_3^{(1)}(z_s, w) \) is the Taylor remainder term of order three, given by
\[
T_3^{(1)}(z_s, w) := \frac{1}{2} \int_0^1 (1 - t)^2 d^3 H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z) + tw)[w, w, w] dt \tag{5.35}
\]

For later use we record that the third derivative of \( H^{\text{nl}} \) at \( w_0 = (u_0, v_0) \in H^1 \) in direction \( w = (u, v) \) in \( H^1 \) can be computed as
\[
d^3 H^{\text{nl}}(w_0)[w, w, w] = 12 \int_0^1 (u_0 u v^2 + u^2 v_0 v) dx. \tag{5.36}
\]

Substituting for \( w \) the function \( d_1 \Psi^{\text{nl}}(\Pi S z)[z_\perp] \) and taking into account that \( \Psi_L(z) = \Psi^{\text{nl}}(\Pi S z) + d_1 \Psi^{\text{nl}}(\Pi S z)[z_\perp] \) yields
\[
H^{(1)}(z) = H^{\text{nl}}(\Psi_L(z)) = H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z)) + (\nabla H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z)), d\Psi^{\text{nl}}(\Pi S z)[\Pi \perp z])_r \\
+ \frac{1}{2} (d\nabla H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z))[d\Psi^{\text{nl}}(\Pi S z)[\Pi \perp z], d\Psi^{\text{nl}}(\Pi S z)[\Pi \perp z])_r \\
+ T_3^{(1)}(z_s, d\Psi^{\text{nl}}(\Pi S z)[\Pi \perp z])_r. \tag{5.37}
\]

Writing the right hand side of the latter identity in a more convenient form one gets
\[
H^{(1)}(z) = H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z)) + (\Pi \perp (d\Psi^{\text{nl}}(\Pi S z))^t \nabla H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z), \Pi \perp z)_r \\
+ \frac{1}{2} (\Pi \perp (d\Psi^{\text{nl}}(\Pi S z))^t d\nabla H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z))[d\Psi^{\text{nl}}(\Pi S z)[\Pi \perp z], \Pi \perp z)_r \\
+ T_3^{(1)}(z_s, d\Psi^{\text{nl}}(\Pi S z)[\Pi \perp z])_r. \tag{5.37}
\]

Recall that \( H^{\text{nl}} = H^{\text{nl}} \circ \Psi^{\text{nl}} \). Hence by Theorem \( \ref{thm:3} \) one gets
\[
H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z)) = H^{\text{nl}}(I_s, 0). \tag{5.38}
\]

Furthermore by \( \ref{eq:5.13} \),
\[
\Pi \perp (d\Psi^{\text{nl}}(\Pi S z))^t \nabla H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z)) = 0. \tag{5.39}
\]

Next, the term in \( \ref{eq:5.37} \), which is quadratic in \( z_\perp \), can be written as
\[
\frac{1}{2} (\Pi \perp (d\Psi^{\text{nl}}(\Pi S z))^t d\nabla H^{\text{nl}}(\Psi^{\text{nl}}(\Pi S z))[d\Psi^{\text{nl}}(\Pi S z)[\Pi \perp z], \Pi \perp z) \tag{5.40}
\]

Substituting \( \ref{eq:5.38} \)-\( \ref{eq:5.40} \) into \( \ref{eq:5.37} \) then yields
\[
H^{(1)}(z) = H^{\text{nl}}(I_s, 0) + \frac{1}{2} (\Omega^{\text{nl}}(I_s, 0)[z_\perp], z_\perp)_r + P_2^{(1)}(z) + P_3^{(1)}(z) \tag{5.41}
\]

where
\[
\begin{align*}
P_2^{(1)}(z) &:= \frac{1}{2} (\mathcal{R}^{(1)}(z_s)[z_\perp], z_\perp) \tag{5.42} \\
P_3^{(1)}(z) &:= T_3^{(1)}(z_s, d\Psi^{\text{nl}}(\Pi S z)[\Pi \perp z])
\end{align*}
\]
Lemma 5.3. (i) For any $s \in \mathbb{Z}_{\geq 0}$, $\mathcal{P}^{(1)}_{2} : \mathcal{V} \cap h_{r}^{s} \rightarrow \mathbb{R}$ is real analytic and the following estimates hold: for any $s \in \mathbb{Z}_{\geq 0}$, $z \in \mathcal{V} \cap h_{r}^{s}$,

$$\|\nabla \mathcal{P}^{(1)}_{2} (z)\|_{s} \lesssim_{s} \|z\|_{s}$$

and for any $k \in \mathbb{Z}_{\geq 1}$, $\hat{z}_{1}, \ldots, \hat{z}_{k} \in h_{r}^{s}$,

$$\|d^{k} \nabla \mathcal{P}^{(1)}_{2} (z)[\hat{z}_{1}, \ldots, \hat{z}_{k}]\|_{s} \lesssim_{s,k} \sum_{j=1}^{k} \|\hat{z}_{j}\|_{0} \prod_{i \neq j} \|\hat{z}_{i}\|_{0} + \|z\|_{s} \prod_{j=1}^{k} \|\hat{z}_{j}\|_{0}.$$

(ii) For any $s \in \mathbb{Z}_{\geq 0}$, $\mathcal{P}^{(1)}_{3} : \mathcal{V} \cap h_{r}^{s} \rightarrow \mathbb{R}$ is real analytic and the following estimates hold: for any $s \in \mathbb{Z}_{\geq 0}$, $z \in \mathcal{V} \cap h_{r}^{s}$, $\hat{z} \in h_{r}^{s}$,

$$\|\nabla \mathcal{P}^{(1)}_{3} (z)\|_{s} \lesssim_{s} \|z\|_{s} \|z\|_{0}, \quad \|d \nabla \mathcal{P}^{(1)}_{3} (z)[\hat{z}]\|_{s} \lesssim_{s} \|z\|_{s} \|\hat{z}\|_{0} + \|z\|_{0} \|\hat{z}\|_{s}$$

and for any $k \in \mathbb{Z}_{\geq 2}$, $\hat{z}_{1}, \ldots, \hat{z}_{k} \in h_{r}^{s}$,

$$\|d^{k} \nabla \mathcal{P}^{(1)}_{3} (z)[\hat{z}_{1}, \ldots, \hat{z}_{k}]\|_{s} \lesssim_{s,k} \sum_{j=1}^{k} \|\hat{z}_{j}\|_{0} \prod_{i \neq j} \|\hat{z}_{i}\|_{0} + \|z\|_{s} \prod_{j=1}^{k} \|\hat{z}_{j}\|_{0}.$$

Proof. Item (i) follows from Lemma 5.1 and item (ii) from 5.12, (5.35), (5.36), and Theorem 5.1. \hfill \Box

Expansion of $\mathcal{H}^{(2)} := \mathcal{H}^{(1)} \circ \Psi_{C}$

To study the expansion of the composition $\mathcal{H}^{(2)} = \mathcal{H}^{(1)} \circ \Psi_{C}$ of the Hamiltonian $\mathcal{H}^{(1)}$ with the symplectic corrector $\Psi_{C}$, constructed in Section 4, we separately expand the compositions of the terms on the right hand side of the identity (5.41) with $\Psi_{C}$. In addition to the projectors $\Pi_{S}, \Pi_{\perp}$, defined in (3.1), (3.2), we also introduce the following versions of them,

$$\pi_{S} : \mathcal{C}^{S} \times \mathcal{C}^{S} \times h_{\perp}^{0} \rightarrow \mathcal{C}^{S} \times \mathcal{C}^{S}, \quad z = (z_{S}, z_{\perp}) \rightarrow z_{S}, \quad (5.43)$$

$$\pi_{\perp} : \mathcal{C}^{S} \times \mathcal{C}^{S} \times h_{\perp}^{0} \rightarrow h_{\perp}^{0}, \quad z = (z_{S}, z_{\perp}) \rightarrow z_{\perp}. \quad (5.44)$$

Term $H^{nls}(I_{S}, 0)$: It is convenient to define

$$h^{nls}(z_{S}) := H^{nls}(I_{S}, 0) \quad (5.45)$$

where we recall that by (5.8), (5.17)

$$I_{S} = I_{S}(z_{S}) = \frac{1}{2} (x_{j}^{2} + y_{j}^{2}) \bigoplus \mathbb{S}, \quad z_{S} = ((x_{j}), y_{j} \in \mathbb{S}) \in \mathbb{R}^{S} \times \mathbb{R}^{S}.$$

By Corollaries 4.1, 4.2, $\Psi_{C}(z)$, defined for $z \in \mathcal{V}_{f} \cap h_{r}^{0}$, is of the form $\Psi_{C}(z) = z + B_{C}(z) = z + B_{C}^{S}(z) + B_{C}^{C}(z)$. Hence the Taylor expansion of $h^{nls}(\pi_{S} \Psi_{C}(z))$ around $z_{S}$ reads

$$h^{nls}(\pi_{S} \Psi_{C}(z)) = h^{nls}(z_{S}) + \nabla_{S} h^{nls}(z_{S}) \cdot \pi_{S} B_{C}^{S}(z) + \mathcal{P}^{(2a)}_{3}(z), \quad (5.46)$$

where $\mathcal{P}^{(2a)}_{3}(z)$ is the Taylor remainder term of order three, given by

$$\mathcal{P}^{(2a)}_{3}(z) := \nabla_{S} h^{nls}(z_{S}) \cdot \pi_{S} B_{C}^{S}(z) + \int_{0}^{1} (1 - t) d_{S} \nabla_{S} h^{nls}(z_{S} + t \pi_{S} B_{C}(z))[\pi_{S} B_{C}(z)] \cdot \pi_{S} B_{C}(z) \, dt. \quad (5.47)$$

In the next lemma we provide estimates for the Hamiltonian $\mathcal{P}^{(2a)}_{3}(z)$. 

27
Lemma 5.4. For any \( s \in \mathbb{Z}_{\geq 0}, \mathcal{P}_{3}^{(2a)} \circ \Psi_{C} : \mathcal{V}_{3}^{\perp} \cap h_{c}^{e} \to \mathbb{R} \) is real analytic. Furthermore, \( \nabla \mathcal{P}_{3}^{(2a)} \) satisfies the following tame estimates: for any \( s \in \mathbb{Z}_{\geq 0}, z \in \mathcal{V}_{3}^{\perp} \cap h_{c}^{e}, \)

\[
\left\| \nabla \mathcal{P}_{3}^{(2a)}(z) \right\|_{s} \lesssim \| z \|_{s} \| z_{\perp} \|_{0}, \quad \left\| \nabla \mathcal{P}_{3}^{(2a)}(z) \right\|_{s} \lesssim \| z \|_{s} \| z_{\perp} \|_{0} + \| z_{\perp} \|_{0} \| z_{\perp} \|_{s}
\]

and for any \( k \in \mathbb{Z}_{\geq 2}, \tilde{z}_{1}, \ldots, \tilde{z}_{k} \in h_{c}^{e}, \)

\[
\left\| \nabla^{k} \mathcal{P}_{3}^{(2a)}(z) \right\|_{s,k} \lesssim_{s,k} \sum_{j=1}^{k} \left\| \tilde{z}_{j} \right\|_{s} \prod_{i \neq j} \left\| \tilde{z}_{i} \right\|_{0} + \left\| z_{\perp} \right\|_{s} \prod_{j=1}^{k} \left\| \tilde{z}_{j} \right\|_{0}.
\]

Proof. The Lemma follows by differentiating \( \mathcal{P}_{3}^{(2a)} \) and applying the estimates of Corollaries 4.1, 4.2. \( \square \)

Term \( \mathcal{H}_{\Omega}(z) := \frac{1}{2} (\Omega_{\perp}^{nl}(I_{S}, 0)z_{\perp}, z_{\perp}) \). To begin with let us point out that the expansion of the composition of the term \( \mathcal{H}_{\Omega}(z) \) with the transformation \( \Psi_{C} \) needs special care. To expain this in more detail, write \( 2\mathcal{H}_{\Omega}(z) \) in the form

\[
(\Omega_{\perp}^{nl}(I_{S}, 0)z_{\perp}, z_{\perp}) = (D_{z_{\perp}}^{2}z_{\perp}, z_{\perp}) + (\Omega_{\perp}(I_{S}, 0)z_{\perp}, z_{\perp})
\]

where \( D_{z_{\perp}} \) is the diagonal operator defined in (5.48). When composed with \( \Psi_{C} = \varphi_{d} + B_{C} \), the term \( (D_{z_{\perp}}^{2}z_{\perp}, z_{\perp}) \) becomes

\[
(D_{z_{\perp}}^{2}[z_{\perp} + \pi_{\perp}B_{C}(z)], z_{\perp} + \pi_{\perp}B_{C}(z)\rangle_{r} = (D_{z_{\perp}}^{2}[z_{\perp}], z_{\perp})_{r} + (D_{z_{\perp}}^{2}[\pi_{\perp}B_{C}(z)], \pi_{\perp}B_{C}(z))_{r} + (D_{z_{\perp}}^{2}[\pi_{\perp}B_{C}(z)], \pi_{\perp}B_{C}(z))_{r}
\]

(5.48)

where \( \pi_{\perp} \) is defined in (5.44). By (4.20) - (4.30), it then follows that the difference

\[
\frac{1}{2} (D_{z_{\perp}}^{2}[z_{\perp} + \pi_{\perp}B_{C}(z)], z_{\perp} + \pi_{\perp}B_{C}(z))_{r} - \frac{1}{2} (D_{z_{\perp}}^{2}[z_{\perp}], z_{\perp})_{r}
\]

belongs to the error term \( \mathcal{P}_{3}(z) \) in Theorem 4.2. Since \( B_{C} \) is only one smoothing, the two terms

\[
(D_{z_{\perp}}^{2}[z_{\perp}], \pi_{\perp}B_{C}(z))_{r}, \quad (D_{z_{\perp}}^{2}[\pi_{\perp}B_{C}(z)], z_{\perp})_{r}
\]

could prevent that \( \mathcal{P}_{3} \) satisfies the estimates (1.6), stated in Theorem 1.2. To proceed recall that \( \Psi_{C} = \Psi_{X}^{b_{1}} \) where \( \Psi_{X}^{b_{1}} \) is the flow map, defined in (4.10). We have

\[
\mathcal{H}_{\Omega}(\Psi_{C}(z)) = \mathcal{H}_{\Omega}(z) + \mathcal{P}_{3}^{(2a)}(z), \quad \mathcal{P}_{3}^{(2a)}(z) := \mathcal{H}_{\Omega}(\Psi_{C}(z)) - \mathcal{H}_{\Omega}(z).
\]

(5.49)

Using the mean value theorem and recalling (4.10), one has

\[
\mathcal{P}_{3}^{(2a)}(z) = \int_{0}^{1} \mathcal{H}_{\Omega}(\Psi_{X}^{b_{1}}(z), \tau) d\tau
\]

(5.50)

where for any \( \tau \in [0, 1] \), the Hamiltonian \( \mathcal{P}_{\Omega}(z, \tau) \) is defined by

\[
\mathcal{P}_{\Omega}(z, \tau) := (\nabla \mathcal{H}_{\Omega}(z), X(z, \tau))_{r}.
\]

(5.51)

One has that

\[
(\nabla \mathcal{H}_{\Omega}(z), X(z, \tau))_{r} = \frac{1}{2} \nabla_{S} \mathcal{H}_{\Omega}(z) \cdot \pi_{S} X(z, \tau) + (\Omega_{\perp}^{nl}(I_{S}, 0)z_{\perp}, \pi_{\perp}X(z, \tau))_{r}. \quad \text{(5.52)}
\]

By (4.12), the vector field \( X(z, \tau) \) was chosen to be

\[
X(z, \tau) = -L_{\tau}(z)^{-1}E(z)
\]
where $E(z)$ is given by (4.10) and $L_r(z)^{-1}$ by the Neumann series (4.9) in Lemma 4.1. Hence

$$X(z, \tau) = -L_r(z)^{-1}E(z) = -J E(z) - \sum_{n\geq 1} (-1)^n \tau^n (JL(z))^n JE(z)$$

$$= -J E(z) + \tau JL(z) \sum_{n\geq 0} (-1)^n \tau^n (JL(z))^n JE(z)$$

$$= -J E(z) + \tau JL(z)X(z, \tau). \quad (5.53)$$

Since $E = \Pi_S E$ and $J^t = -J$, the last term in (5.52) becomes

$$\left(\Omega^{nls}_+(I_S, 0)\right)_{z, \perp} = (\Omega^{nls}_+(I_S, 0)z, \pi_\perp \tau JL(z)X(z, \tau)) = -\tau \left(\Omega^{nls}_+(I_S, 0)z, \pi_\perp L(z)X(z, \tau)\right). \quad (5.54)$$

By (3.30), the component $L^j_+(z)$ of $L(z)$ vanishes. Hence using the projections introduced in (5.53), (5.54), one has

$$\pi_\perp L(z)X(z, \tau) = L^S_+(z)\pi_S X(z, \tau).$$

Substituting the latter expression into (5.53), then leads to

$$\left(\Omega^{nls}_+(I_S, 0)\right)_{z, \perp} = (\pi_\perp \tau L^S_+(z)J\Omega^{nls}_+(I_S, 0)z, \pi_\perp \pi_S X(z, \tau))$$

$$\underbrace{\tau L^S_+(z)\pi S_+(I_S, 0)z, \pi_\perp \pi_S X(z, \tau)} = \tau L^S_+(z)\pi S_+(I_S, 0)z, \pi_\perp \pi_S X(z, \tau). \quad (5.55)$$

Note that by the definition (3.32),

$$L^S_+(z)\pi S_+(I_S, 0)z = \left(\begin{array}{c}
\langle i \left[ d_\perp \Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]]_r\rangle_{\psi} \rangle_{r} \end{array}\right)_{\perp}.$$

Let us take a closer look at the expression

$$d_\perp \Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z] = d\Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]].$$

Substituting for $\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]$, one gets

$$d\Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z] = d\Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]]_r = \underbrace{d\Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]].$$

Note that the first term on the right hand side of the latter identity can be simplified. Since $\Psi^{nls}$ is symplectic,

$$d\Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]_r = \begin{cases} \mathbb{I}, & \text{if } \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}] \end{cases},$$

one has

$$d\Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}] = \underbrace{d\nabla H^{nls}(\Psi^{nls}(\Pi_S z)) d\Psi^{nls}(\Pi_S z) [z, \hat{\pi}]. \quad (5.57)}$$

Combining the above identities, the component $i \langle d_\perp \Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]_r$ on the right hand side of (5.58) becomes, for $j \in S$ arbitrary,

$$i \langle d_\perp \Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]_r = \langle d\nabla H^{nls}(\Psi^{nls}(\Pi_S z)) d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}], \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]_r$$

$$- i \langle d_\perp \Psi^{nls}(\Pi_S z) [\Omega^{nls}_+(I_S, 0)z, \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]_r = \langle d\nabla H^{nls}(\Psi^{nls}(\Pi_S z)) d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}], \partial_{\psi} d_\perp \Psi^{nls}(\Pi_S z) [z, \hat{\pi}]_r \quad (5.58)$$
which in view of $d\nabla H^{\text{nlS}}(w) = D_2 + d\nabla H_4^{\text{nlS}}(w)$ (cf. (5.33)) leads to

$$i\left<\bar{\partial}_z \Psi^{\text{nlS}}(\Pi z) | J^\perp(I_S, 0) z_\perp, \partial_z d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r$$

$$+ \partial_x d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp, \partial_z d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r$$

$$= \left< D_2 d_\perp \Psi^{\text{nlS}}(z, 0) | z_\perp, \partial_z d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r$$

$$- \partial_x d_\perp \Psi^{\text{nlS}}(\Pi z) | J^\perp(I_S, 0) z_\perp, \partial_z d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r.$$  

(5.59)

Since $D_2 = D_2^r$, the first term on the right hand side on the latter identity can be written as

$$\left< D_2 d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp, \partial_z d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r = \frac{1}{2} \partial_x \left< D_2 d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp, d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r$$

$$= \frac{1}{2} \partial_x \left< \omega(z) | 0, z_\perp\right>_r$$

$$= \frac{1}{2} \partial_x \left< (d_\perp \Psi^{\text{nlS}}(\Pi z))^\dagger D_2 d_\perp \Psi^{\text{nlS}}(\Pi z) | 0, z_\perp\right>_r.$$

(5.60)

which can be further transformed as follows: using $D_2 = d\nabla H^{\text{nlS}} - d\nabla H_4^{\text{nlS}}$ (cf. (5.33)) and taking into account that by (5.25)

$$(d_\perp \Psi^{\text{nlS}}(z, 0))^\dagger d\nabla H^{\text{nlS}}(\Psi^{\text{nlS}}(z, 0)) d_\perp \Psi^{\text{nlS}}(z, 0) | 0, z_\perp = \Omega^{\text{nlS}}(I_S, 0) | 0, z_\perp | + R^\perp(I_S, z_\perp)$$

one lead to

$$\frac{1}{2} \partial_x \left< (d_\perp \Psi^{\text{nlS}}(\Pi z))^\dagger D_2 d_\perp \Psi^{\text{nlS}}(\Pi z) | 0, z_\perp\right>_r = \frac{1}{2} \partial_x \left< \Omega^{\text{nlS}}(I_S, 0) | 0, z_\perp\right>_r$$

$$+ \frac{1}{2} \partial_x \left< (d_\perp \Psi^{\text{nlS}}(\Pi z))^\dagger d\nabla H_4^{\text{nlS}}(\Psi^{\text{nlS}}(\Pi z)) d_\perp \Psi^{\text{nlS}}(z, 0) | z_\perp, d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r.$$

Let us analyze $\partial_x \left< \Omega^{\text{nlS}}(I_S, 0) | 0, z_\perp\right>_r$ in more detail. Substituting for $\Omega^{\text{nlS}}(I_S, 0)$ the expression $D_2^2 + \Omega^{\text{nlS}}(I_S, 0)$ (cf. (5.24)) and using that $\left< \partial_x D_2^2 z_\perp, z_\perp\right>_r = 0$ for any $j \in S$, one concludes that

$$\left< \partial_x \Omega^{\text{nlS}}(I_S, 0) z_\perp, z_\perp\right>_r = 0, \quad \forall j \in S.$$  

The above identities then imply that (5.60) becomes

$$\left< D_2 d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp, \partial_z d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r = \frac{1}{2} \left< \partial_x \Omega^{\text{nlS}}(I_S, 0) z_\perp, z_\perp\right>_r$$

$$+ \frac{1}{2} \left< \partial_x R^\perp(I_S, 0) z_\perp, z_\perp\right>_r$$

$$= \frac{1}{2} \left< \partial_x \Omega^{\text{nlS}}(I_S, 0) z_\perp, z_\perp\right>_r.$$  

(5.61)

With (5.60) - (5.61), the identity (5.59) becomes

$$i\left< d_\perp \Psi^{\text{nlS}}(\Pi z) | J^\perp(I_S, 0) z_\perp, \partial_z d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r = \left< R^\perp(I_S, 0) z_\perp, z_\perp\right>_r,$$

(5.62)

where for any $j \in S$, $R^\perp(I_S, z) : h^\perp_{1c} \rightarrow h^\perp_{1c}$ is the linear operator defined by

$$\frac{1}{2} \partial_x \Omega^{\text{nlS}}(I_S, 0) + \frac{1}{2} \pi_1 \partial_x R^\perp(I_S, 0) z_\perp - \frac{1}{2} \partial_x \left< (d_\perp \Psi^{\text{nlS}}(z, 0))^\dagger d\nabla H_4^{\text{nlS}}(\Psi^{\text{nlS}}(\Pi z)) d_\perp \Psi^{\text{nlS}}(z, 0) - i \left< \partial_x d_\perp \Psi^{\text{nlS}}(\Pi z)\right>_r d\nabla H_4^{\text{nlS}}(\Psi^{\text{nlS}}(\Pi z)) d_\perp \Psi^{\text{nlS}}(\Pi z)\right>_r.$$  

(5.63)

Arguing similarly as above one obtains

$$i\left< d_\perp \Psi^{\text{nlS}}(\Pi z) | J^\perp(I_S, 0) z_\perp, \partial_y d_\perp \Psi^{\text{nlS}}(\Pi z) | z_\perp\right>_r = \left< R^{\perp}_y z_\perp, z_\perp\right>_r,$$

(5.64)
where $\mathcal{R}_{y_j}(z_S) : h^0_{-c} \to h^0_{-c}$ is given by

$$
\frac{1}{2} \partial_y \Omega_{\perp}^{(0)}(I_S, 0) + \frac{1}{2} \pi_\perp \partial_y \mathcal{R}_{x_j}^{(1)}(z_S) = \frac{1}{2} \pi_\perp \partial_y ((d_\perp \Psi^{nls}(z_S, 0))^t d_\perp \mathcal{H}_4^{nls} (\Psi^{nls}(\Pi_S z)) d_\perp \Psi^{nls}(\Pi_S z)) + \\
(\partial_y d_\perp \Psi^{nls}(\Pi_S z))^t d_\perp \mathcal{H}_4^{nls} (\Psi^{nls}(\Pi_S z)) d_\perp \Psi^{nls}(\Pi_S z) - i(\partial_y d_\perp \Psi^{nls}(\Pi_S z))^t \partial_\perp \Psi^{nls}(\Pi_S z) J \mathcal{R}_{x_j}^{(1)}(z_S).
$$

(5.65)

In the next lemma we state estimates for the operators $\mathcal{R}_{x_j}(z_S)$ and $\mathcal{R}_{y_j}(z_S)$.

**Lemma 5.5.** For any $j \in S$ and $s \in \mathbb{Z}_{\geq 0}$, the maps

$$
\mathcal{R}_{x_j} : \mathcal{V}_S \cap (\mathbb{R}^S \times \mathbb{R}^S) \to \mathcal{L}(h^s_{-c}, h^s_{-c}), \quad \mathcal{R}_{y_j} : \mathcal{V}_S \cap (\mathbb{R}^S \times \mathbb{R}^S) \to \mathcal{L}(h^s_{-c}, h^s_{-c}),
$$

are real analytic and bounded. Furthermore, for any $\alpha, \beta \in \mathbb{Z}^S_{\geq 0}$,

$$
\|\partial_\alpha \partial_\beta \mathcal{R}_{x_j}(z_S)\|_{\mathcal{L}(h^s_{-c}, h^s_{-c})}, \quad \|\partial_\alpha \partial_\beta \mathcal{R}_{y_j}(z_S)\|_{\mathcal{L}(h^s_{-c}, h^s_{-c})} \lesssim s, \alpha, \beta, 1.
$$

**Proof.** The lemma follows from Theorem 1.1 and Lemmata 5.1, 5.2.

Finally, by (5.51), (5.52), (5.53), (5.56), (5.62), and writing

$$
\pi_S X(z, \tau) = ((X_j(z, \tau))_{j \in S}, (X_j(z, \tau))_{j \in S}) \in \mathbb{R}^S \times \mathbb{R}^S
$$

one sees that the Hamiltonian $\mathcal{P}_\Omega(z, \tau)$, defined by (5.51), can be written in the form

$$
\frac{1}{2} \nabla_S \Omega(z) \cdot \pi_S X(z, \tau) + \sum_{j \in S} X_{j, \tau}(z, \tau) (\mathcal{R}_{x_j}(z_S)[z_{\perp}], z_\perp)_r + \sum_{j \in S} X_{j, \tau}(z, \tau) (\mathcal{R}_{y_j}(z_S)[z_{\perp}], z_\perp)_r.
$$

(5.66)

In the next lemma we state estimates for the Hamiltonian $\mathcal{P}_3^{(2b)}$, defined in (5.50).

**Lemma 5.6.** For any $s \in \mathbb{Z}_{\geq 0}$, the Hamiltonian $\mathcal{P}_3^{(2b)} : \mathcal{V}_S \cap (\mathbb{R}^S \times \mathbb{R}^S) \to \mathbb{R}$ is real analytic. Moreover, it satisfies the following tame estimates: for any $s \in \mathbb{Z}_{\geq 0}$, $z \in \mathcal{V}_S \cap h^s_{-c}, \tilde{z}_1, \tilde{z}_2 \in h^s_{-c}$,

$$
\|\nabla \mathcal{P}_3^{(2b)}(z)\| \lesssim_s s, \|z_{\perp}\|_0, \|z_{\perp}\|_0, \|\tilde{z}_{\perp}\|_0, \|\tilde{z}_{\perp}\|_0 + \|z_{\perp}\|_0 \|\tilde{z}_{\perp}\|_0, \\
\|d^2 \nabla \mathcal{P}_3^{(2b)}(z)\| \lesssim_s s, \|z_{\perp}\|_0 \|\tilde{z}_{\perp}\|_0 + \|z_{\perp}\|_0 \|\tilde{z}_{\perp}\|_0 + \|z_{\perp}\|_0 \|\tilde{z}_{\perp}\|_0 + \|z_{\perp}\|_0 \|\tilde{z}_{\perp}\|_0, \\
\|d^k \mathcal{P}_3^{(2b)}(z)\| \lesssim_s s, \|z_{\perp}\|_0 + \|z_{\perp}\|_0, \|\tilde{z}_{\perp}\|_0.
$$

(5.67)

and for any $k \in \mathbb{Z}_{\geq 2}$, $\tilde{z}_1, \ldots, \tilde{z}_k \in h^s_{-c}$,

$$
\|d^k \mathcal{P}_3^{(2b)}(z)\| \lesssim_s \sum_{s, k} \sum_{\|\tilde{z}_1\|_0, \ldots, \|\tilde{z}_k\|_0} k \prod_{j=1}^k \|\tilde{z}_j\|_0.
$$

**Proof.** The lemma follows by (5.50), (5.66), and Lemmata 5.1, 5.2, 5.5.

**Term $\mathcal{P}_2^{(1)}$:** Recall that the Hamiltonian $\mathcal{P}_2^{(1)}$ was introduced in (5.42). For $z \in \mathcal{V}_S \cap h^0_{-c}$ one has $\Psi_C(z) = z + B_C(z)$ and hence the Taylor expansion of $\mathcal{P}_2^{(1)}(\Psi_C(z))$ around $z$ reads

$$
\mathcal{P}_2^{(1)}(\Psi_C(z)) = \mathcal{P}_2^{(1)}(z) + \mathcal{P}_3^{(2c)}(z), \quad \mathcal{P}_3^{(2c)}(z) := \int_0^1 (\nabla \mathcal{P}_2^{(1)}(z + tB_C(z)), B_C(z))_r dt.
$$

The following lemma holds:
Lemma 5.8. For any $s \in \mathbb{Z}_{\geq 0}$, the Hamiltonian $P_2^{(1)} \circ \Psi_C : V_0^s \cap h^s_0 \to \mathbb{R}$ is real analytic. Moreover, the Hamiltonian $P_3^{(2c)}$, defined in \(5.67\), satisfies the following tame estimates: for any $s \in \mathbb{Z}_{\geq 0}$, $z \in V_0^s \cap h^s_0$, $\tilde{z} \in h^s_o$,

$$
\|\nabla P_3^{(2c)}(z)\|_s \lesssim_s \|z\|_s \|z\|_0, \quad \|d\nabla P_3^{(2c)}(z)[\tilde{z}]\|_s \lesssim_s \|z\|_s \|\tilde{z}\|_0 + \|z\|_0 \|\tilde{z}\|_s, 
$$

and for any $k \in \mathbb{Z}_{\geq 2}$, $\tilde{z}_1, \ldots, \tilde{z}_k \in h^s_0$,

$$
\|d^k \nabla P_3^{(2c)}(z)[\tilde{z}_1, \ldots, \tilde{z}_k]\|_s \lesssim_{s,k} \sum_{j=1}^k \|\tilde{z}_j\|_s \prod_{i \neq j} \|\tilde{z}_i\|_0 + \|z\|_s \|\tilde{z}\|_0.
$$

Proof. The lemma follows by differentiating $P_3^{(2c)}$ and applying Corollary 4.1 and Lemma 5.3 (i).

**Term $P_3^{(1)}$:** By \([5.44]\), $P_3^{(1)}$ is given by $T_3^{(1)}(z, d\Psi^{nls}(\Pi_S z) [\Pi_\perp z])$ where $T_3^{(1)}$ is the Taylor remainder term of order three, introduced in \([5.35]\). Using the estimates of $P_3^{(1)}$ of Lemma 5.3 (ii), the Hamiltonian $P_3^{(1)} \circ \Psi_C$ can be estimated as follows:

Lemma 5.8. For any $s \in \mathbb{Z}_{\geq 0}$, $P_3^{(1)} \circ \Psi_C : V_0^s \cap h^s_0 \to \mathbb{R}$ is real analytic. Moreover, the following tame estimates hold: for any $s \in \mathbb{Z}_{\geq 1}$, $z \in V_0^s \cap h^s_0$, $\tilde{z} \in h^s_0$,

$$
\|\nabla (P_3^{(1)} \circ \Psi_C)(z)\|_s \lesssim_s \|z\|_s \|z\|_0, \quad \|d\nabla (P_3^{(1)} \circ \Psi_C)(z)[\tilde{z}]\|_s \lesssim_s \|z\|_s \|\tilde{z}\|_0 + \|z\|_0 \|\tilde{z}\|_s, 
$$

and for any $k \in \mathbb{Z}_{\geq 2}$, $\tilde{z}_1, \ldots, \tilde{z}_k \in h^s_0$,

$$
\|d^k \nabla (P_3^{(1)} \circ \Psi_C)(z)[\tilde{z}_1, \ldots, \tilde{z}_k]\|_s \lesssim_{s,k} \sum_{j=1}^k \|\tilde{z}_j\|_s \prod_{i \neq j} \|\tilde{z}_i\|_0 + \|z\|_s \|\tilde{z}\|_0.
$$

Proof. The lemma follows by differentiating the Hamiltonian $P_3^{(1)} \circ \Psi_C$ and applying Corollary 4.1 and Lemma 5.3 (ii).

By \([5.41], \ [5.41], \ [5.49], \ [5.67]\) one gets that the Hamiltonian $H^{(2)} := H^{(1)} \circ \Psi_C = H^{nls} \circ \Psi_L \circ \Psi_C$ has the form

$$
H^{(2)}(z) = H^{nls}(I_S, 0) + \frac{1}{2} (\Omega^{nls}(I_S, 0) [z]_\perp)_s + P_2(z) + P_3(z) \tag{5.68}
$$

where for any $z \in V_0^s \cap h^s_0$,

$$
P_2(z) := \nabla_S h^{nls}(z) \cdot \pi_S B^C_2(z) + P_2^{(1)}(z), \tag{5.69}
$$

$$
P_3(z) := T_3^{(2a)}(z) + P_3^{(2a)}(z) + P_3^{(2c)}(z) + P_3^{(1)}(\Psi_C(z)). \tag{5.70}
$$

Note that $P_2$ is quadratic with respect to $z_\perp$, whereas $P_3$ is a remainder term of order three in $z_\perp$. Being quadratic with respect to $z_\perp$, $P_2$ can be written as

$$
P_2(z) = \frac{1}{2} (d_\perp(\nabla_\perp P_2(\Pi_S z))[z]_\perp)_s.
$$

We prove the following

**Lemma 5.9.** The Hamiltonian $P_2$ vanishes on $V_0^s \cap h^s_0$.
Proof. By Corollary 4.4, \( \Psi_C(\Pi S z) = \Pi S z \) and \( d\Psi_C(\Pi S z) = \text{Id} \). Hence by the chain rule and formula (5.5), the map \( \Psi = \Psi_L \circ \Psi_C \) satisfies

\[
d\Psi(\Pi S z) = d\Psi_L(\Pi S z) = d\Psi^{nls}(\Pi S z).
\]

(5.71)

Recall that we denoted by \( \hat{\omega}(t) \) the solution of equation (5.20), obtained by linearizing the dNLS equation along \( w(t) = \Psi^{nls}(\Pi S z(t)) \) with initial data \( \hat{\omega}(0) = \Psi^{nls}(\Pi S z(t))(0, \hat{z}^{(0)}_\perp) \) and by \( \hat{z}(t) = (0, \hat{z}_\perp(t)) \) the one of the equation obtained by linearizing the dNLS equation, expressed in Birkhoff coordinates (cf (5.14)), along \( (z_S(t), 0) = \Pi S z(t) \) with initial data \( (0, \hat{z}^{(0)}_\perp) \). Since \( \Psi^{nls} \) is symplectic, \( \hat{\omega}(t) = \Psi^{nls}(\Pi S z(t))(\hat{z}(t)) \). We remark that \( (z_S(t), 0) = \Pi S z(t) \) is also a solution of the Hamiltonian equation \( \partial_t z^{(2)} = J\nabla H^{(2)}(z^{(2)}) \) with \( H^{(2)} \) given by (5.68). Denote by \( \hat{z}^{(2)}(t) = (0, \hat{z}^{(2)}_\perp(t)) \) the solution of the equation obtained by linearizing \( \partial_t \hat{z}^{(2)} = J\nabla H^{(2)}(z^{(2)}) \) along \( \Pi S z(t) \) with the same initial data \( (0, \hat{z}^{(0)}_\perp) \) as above. Since \( \Psi \) is symplectic, \( \hat{\omega}(t) = \Psi(\Pi S z(t))(\hat{z}^{(2)}(t)) \), implying together with \( \Psi(\Pi S z) = \Psi^{nls}(\Pi S z) \) (cf (5.71) above) that \( \hat{z}^{(2)}(t) = \hat{z}(t) \) for any \( t \). By (5.13), \( \hat{z}_\perp(t) \) satisfies

\[
\partial_t \hat{z}_\perp(t) = J\nabla H^{(2)}(I_S, 0)[\hat{z}_\perp(t)]
\]

(5.72)

whereas by (5.68), one has

\[
\partial_t \hat{z}^{(2)}_\perp(t) = Jd_\perp \nabla H^{(2)}(\Pi S z(t))[\hat{z}^{(2)}_\perp(t)] = J\Omega^{nls}_\perp(I_S, 0)[\hat{z}^{(2)}_\perp(t)] + Jd_\perp \nabla_\perp \mathcal{P}_3(\Pi S z(t))[\hat{z}^{(2)}_\perp(t)] .
\]

(5.73)

In particular, it follows that \( d_\perp \nabla_\perp \mathcal{P}_3(\Pi S z(0))[\hat{z}^{(0)}_\perp] = 0 \). Since \( \mathcal{P}_3(z) \) is quadratic in \( z_\perp \) and the initial data \( \eta_S(0) \in \mathcal{V}_\perp^{0} \cap h^0_{\perp} \), \( \hat{z}^{(0)}_\perp \in h^0_{\perp} \) are arbitrary, it follows that \( \mathcal{P}_3(z) = 0 \) for any \( z \in \mathcal{V}_\perp^{0} \cap h^0_{\perp} \), which proves the claimed statement.

As a consequence of Lemma 5.9 formula (5.68) becomes

\[
H^{(2)}(z) = H^{nls}(I_S, 0) + \frac{1}{2} \left( \Omega^{nls}_\perp(I_S, 0)[z_\perp], z_\perp \right) + \mathcal{P}_3(z) .
\]

(5.74)

The Hamiltonian \( \mathcal{P}_3 \), introduced in (5.70), satisfies the following tame estimates.

**Lemma 5.10 (Tame estimates of \( \mathcal{P}_3 \)).** For any \( s \in \mathbb{Z}_{\geq 0} \), the Hamiltonian \( \mathcal{P}_3 : \mathcal{V}_\perp^{0} \cap h^0_{\perp} \rightarrow \mathbb{R} \) is real analytic and satisfies the following tame estimates: for any \( z \in \mathcal{V}_\perp^{0} \cap h^0_{\perp} \), \( \hat{z} \in h^0_{\perp} \),

\[
\| \nabla \mathcal{P}_3(z) \|_s \lesssim_s \| z_\perp \|_s \| z_\perp \|_0 \quad \text{and} \quad \| d_\perp \nabla_\perp \mathcal{P}_3(z)[\hat{z}] \|_s \lesssim_s \| z_\perp \|_s \| \hat{z} \|_0 + \| z_\perp \|_0 \| \hat{z} \|_s
\]

and for any \( k \in \mathbb{Z}_{\geq 2} \), \( \hat{z}_1, \ldots, \hat{z}_k \in h^0_{\perp} \),

\[
\| d^k \nabla \mathcal{P}_3(z)[\hat{z}_1, \ldots, \hat{z}_k] \|_s \lesssim_s \sum_{j=1}^k \| \hat{z}_j \|_s \prod_{i \neq j} \| \hat{z}_i \|_0 + \| \hat{z}_j \|_0 \prod_{j=1}^k \| \hat{z}_j \|_0
\]

Proof. The claimed statements follow from Lemmata 5.4, 5.6, 5.7 and 5.8.

5.3 **Summary of the proof of Theorem 1.2**

Theorem 1.2 is a direct consequence of Propositions 5.1, 5.2, formula (5.74), and Lemma 5.10.

6 **Proof of Theorem 1.3**

Within this proof, it is convenient to use complex Birkhoff coordinates, given by \( \zeta_n := (x_n - i y_n)/\sqrt{2} \), \( n \in \mathbb{Z} \). A solution \( z(t) = (x(t), y(t)) \) of the dNLS equation in Birkhoff coordinates then satisfies the equations

\[
\partial_t \zeta_n = -i \omega_n^{nls} \zeta_n, \quad n \in \mathbb{Z},
\]

(6.1)
We now consider the special solutions
\[ \Psi_{\text{nls}}. \]

Since \( \Psi \)
Note that the latter equation are reduced to constant coefficients and hence
\[ \hat{\zeta}_S(t) \equiv 0, \quad \partial_t \hat{\zeta}_n(t) = -i\omega_n^{\text{nls}}(I_S, 0) \hat{\zeta}_n(t), \quad n \in S^\perp. \]

Note that these solutions are periodic in time and that
\[ \text{Linearize (6.1) at a solution } \]
\[ \text{where } \]
\[ \text{Furthermore, by Theorem 1.1, } \]
\[ \text{Appendix B) and natural identifications (such as the identifications of action angle with Birkhoff coordinates), } \]
\[ \text{the map } \Phi(\ ) \]
\[ \text{is a complete set of Floquet solutions in the sense of [14]. One then concludes that up to normalisations (cf } \]
\[ \text{Remark 6.1. In the terminology of [14], the system of the Floquet exponents } \pm \omega_j(I_S, 0), \quad j \in S^\perp, \text{ is } \]
\[ \text{nonresonant – see e.g. [2] where the relevant properties of the dNLS frequencies are discussed. } \]

7 Appendix A: a version of the Poincaré lemma

We follow the general approach of [16], Chapter V, and restrict to the finite dimensional setup as the extension to infinite dimension is straightforward by restriction, see [14], Lemma 1.1. Let \( E = \mathbb{R}^n \)
and denote by \( L^r_\omega(E) \) the space of multilinear continuous alternating forms of degree \( 0 \leq r \leq n \). Let \( U \subseteq E \) be an open nonempty set and consider
\[ \omega : U \to L^r_\omega(E). \]

For any \( z \in U \), denote by
\[ \omega(z)[\xi_1, \ldots, \xi_r] \in \mathbb{R} \]
the value of \( \omega(z) \) when evaluated at \( \xi_1, \ldots, \xi_r \in E \). Similarly, if \( \xi_j = \xi_j(z) \in E \), \( j = 1, \ldots, r \), are vector fields on \( U \), then we denote by \( \omega[\xi_1, \ldots, \xi_r] \) the function

\[
U \to \mathbb{R}, \quad z \mapsto \omega(z)[\xi_1(z), \ldots, \xi_r(z)].
\]

Furthermore, we denote by \( \omega'(z) : \xi, \xi \in E \), the alternating form

\[
\partial_z \big|_{z=0} \omega(z + \varepsilon\xi) \in L^1_\omega(E).
\]

The exterior differential \( d\omega \), evaluated at \( z \in U, \xi_1, \ldots, \xi_{r+1} \in E \), is then given by the formula

\[
\sum_{j=1}^{r+1} (-1)^{j+1} \omega'(z) : \xi_j[\xi_1, \ldots, \hat{\xi}_j, \ldots, \xi_{r+1}],
\]

also referred to as Cartan’s formula. Let us now consider the case where

\[
E = \mathbb{R}^{n_1} \times \mathbb{R}^{n_2}, \quad n = n_1 + n_2, \quad n_2 \geq 1,
\]

\[
U = U_1 \times U_2 \subseteq \mathbb{R}^{n_1} \times \mathbb{R}^{n_2},
\]

and \( U_2 \) is a ball in \( \mathbb{R}^{n_2} \) centered at 0. We denote the elements of \( U \) by \( z = (x, y) \) and the ones of \( E \) by \( \xi = (v, w) \in \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} \). For any \( r \)-form \( \omega \) on \( U \), denote by \( \omega_C \) the \((r - 1)\)-form on \( U \), obtained by the cone construction: for any \( x \in U_1, y \in U_2, v_1, \ldots, v_{r-1} \in \mathbb{R}^{n_1} \), and \( w_1, \ldots, w_{r-1} \in \mathbb{R}^{n_2} \),

\[
\omega_C(x, y)[(v_1, w_1), \ldots, (v_{r-1}, w_{r-1})] = \int_0^1 \omega(x, ty)[(0, y), (v_1, tw_1), \ldots, (v_{r-1}, tw_{r-1})] \, dt.
\]

Note that since \( U_2 \) is a ball in \( \mathbb{R}^{n_2} \), centered at 0, for any \( 0 \leq t \leq 1, (x, ty) \) is in \( U_1 \times U_2 \) and hence \( \omega(x, ty) \) in (7.3) is well defined.

**Lemma 7.1 (Poincaré lemma).** Assume that \( \omega \) is a \( r \)-form on \( U = U_1 \times U_2 \), with \( 1 \leq r \leq n \) and \( n_2 \geq 1 \), satisfying

\[
\omega(x, 0)[(v_1, 0), \ldots, (v_r, 0)] = 0, \quad \forall x \in U_1, \quad \forall v_1, \ldots, v_r \in \mathbb{R}^{n_1}.
\]

Then

\[
d(\omega_C) + (d\omega)_C = \omega.
\]

In particular, if in addition \( \omega \) is closed, \( d\omega = 0 \), then \( d(\omega_C) = \omega \).

**8 Appendix B: formulas for \( d\Psi^{nls}(zS, 0)[(0, z_\perp)] \)**

Note that for \( z = (z_S, z_\perp) \) with \( z_S \in \mathbb{R}^S \times \mathbb{R}^S \) and \( z_\perp = ((x_j)_{j \in S^+}, (y_j)_{j \in S^+}) \in h_{r+1}^0 \),

\[
d\Psi^{nls}(z_S, 0)[(0, z_\perp)] = \sum_{j \in S^+} x_j d\Psi^{nls}(z_S, 0)[e^{(1,j)}] + \sum_{j \in S^+} y_j d\Psi^{nls}(z_S, 0)[e^{(2,j)}]
\]

where for any \( j \in S^+ \),

\[
e^{(1,j)} = ((\delta_{n_j})_{n \in \mathbb{Z}}, 0), \quad e^{(2,j)} = (0, (\delta_{n_j})_{n \in \mathbb{Z}}).
\]

It turns out that for \( j \in S^+, d\Psi^{nls}(z_S, 0)[e^{(1,j)}] \) and \( d\Psi^{nls}(z_S, 0)[e^{(2,j)}] \) can be computed quite explicitly. Consider the Hamiltonian equation with Hamiltonian given by the coordinate function \( x_j, \partial_t w = i\partial_x x_j \), and denote by \( w(t) \) its solution with initial data \( w(0) = (z_S, 0) \). Then \( z(t) := \Phi^{nls}(w(t)) \) solves

\[
\partial_t z = d\Phi^{nls}(w(t)) \partial_t w(t) = d\Phi^{nls}(w(t)) i\partial_x x_j. \quad (8.1)
\]

Since by Theorem 11.1 \( \Phi^{nls} \) is symplectic, one has \( \partial_t z = J e^{(1,j)} = e^{(2,j)} \). When combined with (8.1) it implies that \( d\Psi^{nls}(z(t))[e^{(2,j)}] = i\partial_x x_j \). Similarly, one derives the corresponding identity for the coordinate function \( y_j \), When evaluated at \( t = 0 \) we then obtain

\[
d\Psi^{nls}(z_S, 0)[e^{(2,j)}] = i\partial_x x_j = (-i\partial_e x_j, i\partial_u x_j), \quad d\Psi^{nls}(z_S, 0)[e^{(1,j)}] = i\partial_y y_j = (-i\partial_e y_j, i\partial_u y_j).
\]
By the definition of $x_j, y_j$ in [9], p 113, one has for a potential $w \in H^1_0$ with Birkhoff coordinates $(z_S, 0)$ (referred to as $S$–gap potential)

$$x_j = \frac{\xi_j}{\sqrt{S}} (e^{i\beta_j} \delta_j^+ + e^{-i\beta_j} \delta_j^-), \quad y_j = \frac{\xi_j}{\sqrt{S}} (e^{i\beta_j} \delta_j^+ - e^{-i\beta_j} \delta_j^-),$$

where $\delta_j^\pm = \gamma_j e^{\pm i\eta_j}$ if $\gamma_j \neq 0$ and $\delta_j^0 = 0$ otherwise. We refer to [9] for the definitions of $\xi_j, \eta_j, \gamma_j$. Since $w$ is assumed to be a $S$–gap potential, it follows that for any $j \in S^\perp$,

$$\partial x_j = \frac{\xi_j}{\sqrt{S}} (e^{i\beta_j} \partial \delta_j^+ + e^{-i\beta_j} \partial \delta_j^-), \quad \partial y_j = \frac{\xi_j}{\sqrt{S}} (e^{i\beta_j} \partial \delta_j^+ - e^{-i\beta_j} \partial \delta_j^-),$$

where by formula (17.3) in [9],

$$\partial \delta_j^\pm = 2 (\partial r_j - \partial \mu_j) \pm (i2\delta(\mu_j) \partial \phi_j + 2\phi_j (i\delta |_{\lambda=\mu_j} + i\delta(\mu_j) \partial \mu_j)).$$

We refer to [9] for the definitions of the various quantities as well as for formulas of the gradients in the latter expression. Each of the two components of these gradients are shown to be a linear combination of quadratic expressions in the entries of the fundamental solution $M = M(x, \lambda)$ of the Zakharov Shabat operator

$$L := \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} \partial_x + \begin{pmatrix} 0 & u \\ u & 0 \end{pmatrix}, \quad w = (u, v) = (u, \bar{u}).$$

In fact, in [10], it has been proved that

$$\partial \delta_j^\pm = ((K_{j2} \pm iH_{j2})^2, (K_{j1} \pm iH_{j1})^2)$$

where

$$H_j = (H_{j1}, H_{j2}) = \frac{1}{\|M_1 + M_2\|_{L^2}} (M_1 + M_2) |_{\lambda=\mu_j}$$

denotes the $L^2$–normalized eigenfunction of $L$ for the Dirichlet eigenvalue $\mu_j$, $M_1, M_2$ are the two columns of $M$, and $K_j = (K_{j1}, K_{j2})$ is the $L^2$–normalized solution of $LF = \mu_j F$, which is $L^2$–orthogonal to $H_j$ and satisfies the additional normalization condition $-i(K_{j1}(0) - K_{j2}(0)) > 0$.

References


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