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Scope Setting Report
Instrument: ODIN – Neutron Imaging

SUMMARY

This document presents three initial design options for the Neutron Instrument Project ODIN (Optical and Diffraction Imaging with Neutrons). Plans for further upgrades to achieve full instrument performance (staging) are described for each option.

ODIN has been assigned to cost category A (9 M€). It is not possible to deliver ODIN within this cost category in a manner that delivers adequate day one performance and a reasonable, affordable path to world leading performance as outlined in this document as Option 1.

The second design option (Option 2) mainly follows the ODIN Project Proposal. It is important to note that the original proposal already foresees some staging (e.g. diffraction detectors).

A complete instrument with minimal to none further staging is discussed as a third option (Option 3).

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1. OVERVIEW

1.1. Science Case

Neutron Imaging, originally based purely on attenuation, has recently evolved dramatically. Now energy- and polarization-dependent imaging techniques as well as interferometry based approaches can be applied across a broad spectrum of scientific disciplines and applications. ODIN with its outstanding and versatile capabilities will not only push the limits of current applications but will add many more by significantly shifting the boundaries of what can be done today.

Simultaneous structural resolution, novel spatially resolved scattering modalities enabled by the pulsed beam approach, increased sensitivity for low Z elements enabled by intrinsic energy and spatial resolutions are some of the examples. It will help to deepen our understanding of phase transitions in high T_c superconductors and magnetic materials, ion propagation in alternative energy devices, structural anomalies in complex industrial materials, and in the study of biological and polymer membranes among many others. The list is vast and broad as well as the impact in many spheres of industrial and basic research.

The benefit of ODIN's envisioned increased spatial resolution neutron radiography is straightforward: it will enable deeper access to structural and failure analysis in non-destructive testing, material science, cultural heritage etc. The neutron metallurgical studies of the 'Titanic' rivets and the metal structures of the 'Twin Towers' are famous examples. But also studies of, for example, fuel cells or water uptake studies in plant-root systems will benefit with their need to resolve structures in the 5-50 μm range.

Using Bragg edge imaging with tuneable medium to high wavelength resolution ($\Delta\lambda/\lambda$ 1% down to <0.5%), ODIN will provide significantly increased chemical and structural sensitivity. This will contribute to structural phase transition and failure analysis in engineering materials, provide new insights into geological samples (igneous rocks or meteorites for example), and it will also help with provenance and manufacturing studies of invaluable artefacts. In energy research this increased sensitivity will help to understand the processes in rechargeable batteries and hydrogen storage materials.

Relatively new techniques such as phase contrast imaging, dark field neutron imaging and polarized neutron imaging will greatly benefit from ODIN's high brilliance and in particular from the long pulse structure for novel quantitative approaches, making these time-consuming investigations more feasible. These techniques can not only help visualizing inhomogeneities in magnetic fields and structures, magnetic phase transitions, and individual magnetic domains, but enables spatially resolved SANS studies also in soft matter. ODIN will thus enable more efficient and precise 3D measurements of domain structures providing invaluable insights in structure and behavior of magnetic materials and superconductors.

Pioneering neutron imaging techniques, such as Spin-Echo Modulation Small-Angle Neutron Scattering and Far Field Neutron Interferometry, further underline the need for a new neutron imaging instrument with the high overall performance and versatility that ODIN will provide.

Neutron imaging is perhaps the fastest growing field in neutron science. ODIN will offer the widest variety of methods with unmatched capabilities taking advantage of the full flexibility offered by the unprecedented source time-structure and brightness of ESS; it will open up new research and play a central, leading role in the diverse Neutron Imaging community.

1.2. Requirements

The top-level requirements for ODIN [1] reflect the key aspects of the instrument proposal science case [2]; they build the foundation for the target scope of the instrument construction project. In order to fulfil these requirements the following instrument specifications have to be met:

1. ODIN shall be able to cover a neutron wavelength range from 1 to 20 Å.
2. A direct spatial resolution down to 10 μm (3D) shall be achieved.
3. Measurement of sample areas of up to 20×20 cm^2 at once with an intensity homogeneity of more than 75% shall be possible.
4. Different wavelength resolutions of 10%, 1% and down to below 0.5% for spectra from 1 Å to 10 Å and 1 Å to 5.5 Å shall be available, respectively.
5. Bandwidths up to about 4.5 Å and 9 Å in every pulse and single pulse suppression modes shall be freely selectable at least between 1 Å and 20 Å.
6. In kinetic measurements time resolutions below 100 ms shall be achievable.
7. Time resolutions of the order of 1 μs shall be possible in quasi-stroboscopic mode.
8. Gamma and fast neutron background as low as reasonably possible.
9. ODIN shall be able to provide complementary x-ray contrast with comparable spatial resolution (10 μm) relatable to the neutron data with according accuracy when full scope is realized.

1.3. Configuration options

Three configuration options are presented:

1. Option 1: Configuration within cost category A (9.0 M€).

2. Option 2: Configuration to meet scientific requirements for world-class performance. Advice from the Imaging STAP (now Imaging and Engineering) was taken into consideration. Cost: 12.7 M€

3. Option 3: Full technical scope. Note that this includes an option that was foreseen for staging in the original proposal. Cost: 18.5 M€

1.4. Timeline

Fig. 1: Anticipated timeline for ODIN

2. OPTION 1: SCOPE WITHIN COST CATEGORY A (9M€)

2.1. Scope

- Focussing, de-focussing, focussing neutron-guide with m=2-5 coatings
- Sample/detector positioning flexible from 52 to 65 m from moderator
- L/D values (Collimation) between 100-10000
- No chopper system
- Medium and high resolution scintillator based detector set ups
- All necessary associated infrastructure (shielding, cabling, cabins etc)

This scope does **not** meet the top-level requirements for:

- Covered wavelength range
- Wavelength resolution
- Bandwidth selection
- Time of Flight (ToF) imaging techniques (e.g. Bragg Edge Imaging).

Furthermore, it is not easily upgradeable to one that meets the full scope. The neutron guide and shielding are specifically designed to host future chopper system components. However, extensive work inside the bunker, even close to the monolith, is needed to install the originally proposed chopper system that will provide higher state-of-the-art wavelength resolution. Once ESS is up and running, activation of the material inside the bunker will make it much more difficult than initially to install chopper and other components there during an extended period of time. With the given budget constraints, only concrete foundations at the planned chopper positions can be prepared in advance.

The science case for ODIN is based on being a versatile instrument with extended, unprecedented chemical and structural sensitivity. This increased sensitivity is only achievable with a sophisticated chopper system that cannot be included in the given cost category.

Therefore, this scope **does not fulfil** the proposed and envisioned science case for ODIN and the performance of such instrument cannot add to the available and significantly cheaper state-of-the-art at high flux continuous sources.

2.2. Costing

The costing is based on bottom-up calculation of the procurement costs and manpower required for the tasks needed to deliver the higher level PBS items. Numbers are rounded to the nearest 1,000 €. All Non-Labor cost are based on manufacturer quotes, ESS cost book values and contributions [3-4] as well as combined experience. Vacuum equipment included is for instrument specific equipment only. Items in the first column are numbered according to ODIN work units (WU). Costs for Phase1 are Salaries only and are not assigned to specific WUs.

Table 1: Costing for ODIN in Cost Category A, Option 1

	Cost Overview		Labor in Person-Years					
	Non-Labor	**Labor**	**01** Manage-ment	**02** Design	**03** Procurem. Labor	**04** Installation	**05** Cold Com-missioning	**Total**
00 Phase 1	0 €	554,000 €	-	-	-	-	-	**4.5**
02 Neutron Transport	1,760,000 €	414,000 €	0.81	1.11	0.44	0.57	0.36	**3.29**
03 Heavy Shutter	231,000 €	194,000 €	0.50	0.52	0.17	0.19	0.09	**1.47**
04 T0 Chopper	2,000 €	2,000 €	0.00	0.00	0.05	0.05	0.00	**0.10**
05 Choppers	0 €	112,000 €	0.61	0.27	0.11	0.25	0.00	**1.24**
06 Cave Interior	646,000 €	462,000 €	0.94	0.89	0.69	0.49	0.57	**3.58**
07 Add ons (Instr. Specific Equipment)	0 €	0 €	0	0	0	0	0	**0.00**
08 Motion Control and EE	121,000 €	226,000 €	0.83	0.20	0.35	0.27	0.26	**1.91**
09 White beam detectors	198,000 €	65,000 €	0.28	0.25	0.14	0.13	0.04	**0.84**
10 ToF Detectors	0 €	0 €	0.00	0.00	0.00	0.00	0.00	**0.00**
11 Shielding	2,964,000 €	423,000 €	1.21	1.28	0.43	0.25	0.19	**3.36**
12 Instrument Infrastructure	69,000 €	194,000 €	1.08	0.18	0.18	0.13	0.14	**1.71**
13 Vacuum	0 €	140,000 €	0.68	0.11	0.11	0.13	0.08	**1.11**
14 PSS	118,000 €	108,000 €	0.56	0.07	0.12	0.07	0.07	**0.89**
Totals	**6,109,000 €**	**2,895,000 €**	**7.50**	**4.88**	**2.79**	**2.60**	**1.80**	**4.5+19.5**
	9,004,000 €							

2.3. Upgrade/Staging plan

The top priority in this staging plan is to install the wavelength resolution enhancement choppers. Adding specialized setups (add ons) such as Grating Interferometry, Spin-Echo Modulated Small Angle Neutron Scattering (SEMSANS) and Polarizer/Analyzer setup would be next steps. The implementation of an x-ray machine and finally diffraction detector banks with an inner radius of 2 m and a spatial resolution of 3 mm are also foreseen.

2.4. Risk

The obvious main risk with this option is the inability to deliver the presented science case: It will not be possible to match the performance of current state-of-the-art experiments. This configuration is a step backwards from imaging instruments existing today, which will impact ESS' reputation as world leading neutron facility. Other risks are related to delays in finalizing the facility and instrument design as well as potential delays in delivery.

Below are top 5 risks rated high using ESS risk measures (impact x likelihood).

Table 2: Top 5 risks for Option 1

RISK LEVEL	RISK	TREATMENT NAME	TREATMENT	CATEGORY	TREATMENT PLAN
High 5x5	Failure to deliver proposed scientific performance	Lower expectations	Mitigate	Budget, quality and function	Communicate with stakeholders the lowered performance expectations. Begin planning for upgrade and seek funding. Responsible: ODIN Team, ESS management
High 4x5	Conventional Facilities Delay	CF LEVEL ESS-0019533	Observe	Schedule, budget, quality and function	Access to hall 2 is a milestone for ODIN schedule. ODIN team Responsible: CF
		External areas like labs and workshops	Mitigate		External areas will give the opportunity to start pre-installations Responsible: CF
High 3x5	Design according to requirements, delay in monolith insert design	Schedule for external milestone	Observe	Schedule, budget, Quality and function	Follow the progress of the design and project schedule. ODIN Team Responsible: Target
		TARGET LEVEL ESS-0019533	Observe		Focus on Safety, feasibility and requirements Responsible: Target
High 3x5	Late delivery of key components	ODIN schedule	Mitigate	Schedule, budget	Properly assess the delivery time and transportation, also the time that is required for installation and arriving at site. Define the critical path for every component. Responsible: ODIN Team
High 2x4	Unsound integration	Integration plan, Hall EPL, Checklist of activities, work package documentation, interface control document	Observe, Mitigate	Schedule, budget, quality and function	Integration plan is to be considered in work package documentation, detail description of interfaces, schedule and a detail list of activities Responsible: ODIN Team

3. OPTION 2: WORLD CLASS PERFORMANCE

3.1. Scope

The scope within this cost category is:

- Focussing, de-focussing, focussing neutron guide with m=2-5 coatings
- Sample/detector positioning flexible from 52 to 65 m from moderator
- L/D values (Collimation) between 100-10000
- Complete wavelength frame multiplication chopper system
    - T_0 chopper
    - Opposing set of moveable Wavelength Frame Multiplication Choppers
    - Bandpass Chopper
    - Set of five Frame Overlap Choppers
- Medium and high resolution detector setups based on fast scintillator technology
- Time of Flight detector
    - High spatial and time resolution
- All necessary associated infrastructure (shielding, cabling, cabins etc)

This scope meets all the high level requirements and is upgradeable to a configuration that provides the full scope.

The science case will mostly be met by this configuration. The absence of a full suite of advanced setups and sample environments directly limits any experiments that need more sophistication as budgeted here. Additional synergetic information from x-ray radiography and diffraction measurements will not be accessible but upgrades are expected and feasible.

3.2. Costing

The costing is based on bottom-up calculation of the procurement costs and manpower required for the tasks needed to deliver the higher level PBS items. Numbers are rounded to the nearest 1,000 €. All Non-Labor cost are based on manufacturer quotes, ESS cost book values and contributions [3-4] as well as combined experience. Vacuum equipment included is for instrument specific equipment only. Items in the first column are numbered according to ODIN work units (WU). Costs for Phase1 are Salaries only and are not assigned to specific WUs.

Table 3: Costing for ODIN, Option 2

	Cost Overview		Labor in Person-Years					
	Non-Labor	Labor	01 Manage-ment	02 Design	03 Procurem. Labor	04 Installation	05 Cold Com-missioning	Total
00 Phase 1	0 €	554,000 €	-	-	-	-	-	**4.5**
02 Neutron Transport	1,760,000 €	414,000 €	0.91	1.11	0.44	0.57	0.36	**3.39**
03 Heavy Shutter	231,000 €	194,000 €	0.50	0.52	0.17	0.19	0.09	**1.47**
04 T0 Chopper	191,000 €	84,000 €	0.15	0.12	0.09	0.06	0.03	**0.45**
05 Choppers	2,220,000 €	389,000 €	1.09	1.02	0.45	0.26	0.21	**3.03**
06 Cave Interior	745,000 €	544,000 €	1.02	0.97	0.70	0.50	0.57	**3.76**
07 Add ons (Instr. Specific Equipment)	0 €	0 €	0	0	0	0	0	**0.00**
08 Motion Control and EE	132,000 €	247,000 €	0.84	0.21	0.36	0.27	0.26	**1.94**
09 White beam detectors	248,000 €	134,000 €	0.31	0.27	0.19	0.16	0.09	**1.02**
10 ToF Detectors	220,000 €	306,000 €	0.22	0.32	0.35	0.20	0.09	**1.18**
11 Shielding	2,964,000 €	423,000 €	1.21	1.28	0.43	0.25	0.19	**3.36**
12 Instrument Infrastructure	75,000 €	208,000 €	1.08	0.18	0.18	0.13	0.14	**1.71**
13 Vacuum	0 €	146,000 €	0.68	0.11	0.11	0.13	0.08	**1.11**
14 PSS	118,000 €	108,000 €	0.56	0.07	0.12	0.07	0.07	**0.89**
Totals	**8,903,000 €**	**3,751,000 €**	**8.58**	**6.19**	**3.59**	**2.80**	**2.19**	**4.5+23.5**
	12,654,000 €							

3.3. Upgrade/Staging plan

The staging plan for this option consists mainly of adding specialized setups (add ons) such as Grating Interferometry, Spin-Echo Modulated Small Angle Neutron Scattering (SEMSANS) and Polarizer/Analyzer setup (see e.g. [5-6]). The implementation of an x-ray machine and finally diffraction detector banks with an inner radius of 2 m and a spatial resolution of 3 mm are also foreseen. Further minor staging options include additions to sample environment and detector equipment.

3.4. Risks

The main risks for this configuration are delays in delivery of various ESS systems and ODIN components.

Below are top 5 risks rated high using ESS risk measures (impact x likelihood).

Table 4: Top 5 risks for Option 2

RISK LEVEL	RISK	TREATMENT NAME	TREATMENT	CATEGORY	TREATMENT PLAN
High 4x5	Conventional Facilities Delay	CF LEVEL ESS-0019533	Observe	Schedule, budget, quality and function	Access to hall 2 is a milestone for ODIN schedule. ODIN team Responsible: CF
		External areas like labs and workshops	Mitigate		External areas will give the opportunity to start pre-installations Responsible: CF
High 3x5	Design according to requirements, delay in monolith insert design	Schedule for external milestone	Observe	Schedule, budget, Quality and function	Follow the progress of the design and project schedule. ODIN Team Responsible: target
		TARGET LEVEL ESS-0019533	Observe		Focus on Safety, feasibility and requirements Responsible: target
High 3x4	Delivery delays	ODIN schedule	Mitigate	Schedule, budget	Properly assess the delivery time and transportation, also the time that is required for installation and arriving at site. Define the critical path for every component. Responsible: ODIN Team
High 2x4	Unsound integration	Integration plan, Hall EPL, Checklist of activities, work package documentation, interface control document	Observe, Mitigate	Schedule, budget, quality and function	Integration plan is to be considered in work package documentation, detail description of interfaces, schedule and a detail list of activities. Responsible: ODIN Team
High 4x2	Large chopper development late or not feasible	Further chopper system design studies/ simulations	Mitigate, Observe	Design, Quality and function	Re-simulation of complete chopper system, feasibility discussions with manufacturers. Responsible: ODIN Team

4. OPTION 3: FULL SCOPE

4.1. Scope

The full instrument scope consists of:

- Focussing, de-focussing, focussing neutron guide with m=2-5 coatings
- Sample/detector positioning flexible from 52 to 65 m from moderator
- L/D values (Collimation) between 100-10000
- Complete wavelength frame multiplication chopper system
    - T_0 chopper
    - Opposing set of moveable Wavelength Frame Multiplication Choppers
    - Bandpass Chopper
    - Set of five Frame Overlap Choppers
- Medium and high resolution scintillator based detector setups
- Time of Flight detectors
    - Ultrafast
    - Large Field Of View
- Grating interferometry setup
- Polarizer – Analyzer setup
- Spin-Echo Modulation Small Angle Neutron Scattering (SEMSANS) setup
- X-ray generator and x-ray radiography setup
- Diffraction detector banks around ±90°
- All necessary associated infrastructure (shielding, cabling, cabins etc)

This is the full scope for this instrument, which includes options that were foreseen for staging in the original instrument proposal: Specialized setups, X-ray option, Diffraction, Specialized sample environment.

4.2. Costing

The costing is based on bottom-up calculation of the procurement costs and manpower required for the tasks needed to deliver the higher level PBS items. Numbers are rounded to the nearest 1,000 €. All Non-Labor cost are based on manufacturer quotes, ESS cost book values and contributions [3-4] as well as combined experience. Vacuum equipment included is for instrument specific equipment only. Items in the first column are numbered according to ODIN work units (WU). Costs for Phase1 are Salaries only and are not assigned to specific WUs.

Table 5: Costing for ODIN Full Scope, (Option 3)

	Cost Overview		Labor in Person-Years					
	Non-Labor	Labor	01 Manage-ment	02 Design	03 Procurem. Labor	04 Installation	05 Cold Com-missioning	Total
00 Phase 1	0 €	554,000 €	-	-	-	-	-	**4.5**
02 Neutron Transport	1,760,000 €	414,000 €	0.91	1.11	0.44	0.57	0.36	**3.39**
03 Heavy Shutter	231,000 €	194,000 €	0.50	0.52	0.17	0.19	0.09	**1.47**
04 T0 Chopper	191,000 €	84,000 €	0.15	0.12	0.09	0.06	0.03	**0.45**
05 Choppers	2,220,000 €	389,000 €	1.09	1.02	0.45	0.26	0.21	**3.03**
06 Cave Interior	858,000 €	591,000 €	1.02	0.91	0.83	0.81	0.71	**4.27**
07 Add ons (Instr. Specific Equipment)	4,502,000 €	514,000 €	0.91	0.87	0.81	0.51	0.57	**3.66**
08 Motion Control and EE	143,000 €	287,000 €	0.84	0.21	0.36	0.27	0.27	**1.95**
09 White beam detectors	248,000 €	134,000 €	0.31	0.27	0.19	0.16	0.09	**1.02**
10 ToF Detectors	770,000 €	333,000 €	0.23	0.32	0.37	0.22	0.11	**1.18**
11 Shielding	2,964,000 €	423,000 €	1.21	1.28	0.43	0.25	0.19	**3.36**
12 Instrument Infrastructure	80,000 €	239,000 €	1.08	0.18	0.18	0.13	0.14	**1.71**
13 Vacuum	0 €	147,000 €	0.68	0.11	0.11	0.13	0.08	**1.11**
14 PSS	118,000 €	108,000 €	0.56	0.07	0.12	0.07	0.07	**0.89**
Totals	**14,084,000 €**	**4,411,000 €**	**9.48**	**6.98**	**4.54**	**3.63**	**2.91**	**4.5+27.5**
	18,495,000 €							

4.3. Risks

The main risks for this configuration are delays in delivery of various ESS systems and ODIN components in general and more specifically chopper system and diffraction detector system.

Below are top 5 risks rated high using ESS risk measures (impact x likelihood).

Table 6: Risks for Option 3

RISK LEVEL	RISK	TREATMENT NAME	TREATMENT	CATEGORY	TREATMENT PLAN
High 4x5	Conventional Facilities Delay	CF LEVEL ESS-0019533	Observe	Schedule, budget, quality and function	Access to hall 2 is a milestone for ODIN schedule. ODIN team Responsible: CF
		External areas like labs and workshops	Mitigate		External areas will give the opportunity to start pre-installations Responsible: CF
High 4x5	Delivery delays	ODIN schedule	Mitigate	Schedule, budget	Properly assess the delivery time and transportation, also the time that is required for installation and arriving at site. Define the critical path for every component. Responsible: ODIN Team
High 3x5	Design according to requirements, delay in monolith insert design	Schedule for external milestone	Observe	Schedule, budget, Quality and function	Follow the progress of the design and project schedule. ODIN Team Responsible: target
		TARGET LEVEL ESS-0019533	Observe		Focus on Safety, feasibility and requirements Responsible: target
High 2x4	Unsound integration	Integration plan, Hall EPL, Checklist of activities, work package documentation, interface control document	Observe, Mitigate	Schedule, budget, quality and function	Integration plan is to be considered in work package documentation, detail description of interfaces, schedule and a detail list of activities Responsible: ODIN Team
High 4x2	Large chopper development late or not feasible	Further chopper system design studies/ simulations	Mitigate, Observe	Design, Quality and function	Re-simulation of complete chopper system, feasibility discussions with manufacturers. Responsible: ODIN Team

5. REFERENCES

[1] System Requirements Specification, ESS-0054765

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[3] ESS contribution for instrument construction and infrastructure, ESS-0063538

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[5] N. Kardjilov *et al*.: Neutron Imaging in Materials Science, *Materials Today* **14** (6), 248-256 (2012)

[6] M. Strobl *et al*.: Quantitative Neutron Dark-field Imaging through Spin-Echo Interferometry, *Scientific Reports*, **5**, 16576 (2015)