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ESS Instrument Construction Proposal
<<ODIN – Optical and Diffraction Imaging with Neutrons>>

	Name	Affiliation
ESS Instrument WP coordinator	M. Strobl	ESS
ESS Partners	L. Udby, H. Carlsen	KU

The following table is used to track the ESS internal distribution of the submitted proposal.

	Name	Affiliation
Document reviewer	Ken Andersen	ESS
Document approver	Oliver Kirstein	ESS
Distribution (list names)		

DECLARATION

This proposal has benefited from a pan-European collaboration on neutron imaging instrumentation. There are European laboratories that are unable to be involved in this proposal for ODIN at the present stage, although they have the moral right to do so. The author of this proposal has benefited from their collaboration, however their individual contributions are not represented in this proposal. We are confident that in the near future these laboratories will be able and wish to join the ODIN project as co-proposers and partners.

OVERVIEW

The ESS has the unique opportunity to take the technical and scientific leadership in the rapidly developing field of neutron imaging by constructing the world's most advanced neutron imaging instrument with un-paralleled versatility and capabilities to enable new science and address wide ranging problems in industry, environment, commerce, and art that cannot be effectively answered today. In most instances, the proposed instrument named 'ODIN - Optical and Diffraction Imaging with Neutrons' will add orders of magnitude of enhancement in performance when compared to the world's existing leading instruments with regards to spatial resolution and energy-discrimination. ODIN is one of the best choices for a day one instrument because it is ideally suited to the ESS source parameters and is one of the lowest risk to build with immediate significant scientific return. The instrument also exemplifies and strengthens the vision of ESS as the premier facility for the future of neutron science with the potential of providing outstanding technical capability and experimental results of significance from the very beginning. ODIN is based on a strategy that allows the instrument to perform from the first day delivering significant results to all of the stakeholders. ODIN is also expected to be realized at a lower cost than the estimated average for planned instruments at the ESS, and the provided concept and specifications allow participation of many potential partners providing maximum flexibility in the design and construction of the instrument. The instrument concept for ODIN described in this proposal is mature in technical details, planning, and scientific vision, and the instrument is now ready to be built.

ODIN is a unique and first of its kind type of instrument that combines imaging with reciprocal space techniques. Such an instrument design with the desired performance level is possible only because of ESS source strength and characteristics. Despite the novelty of the concept comprising a bi-spectral extraction, a long partly elliptical guide, a complex wavelength-frame-multiplication chopper system, and a flexible end station with various detector solutions, the design is technically complete with remarkably low associated risks. To minimize risks, the designed instrument components are state-of-the-art that will employ proven methods for fabrication and testing. In the case of technical difficulties, alternative solutions are available that can be implemented easily without significant impact on the performance. The flexible end station design allows for keeping up with the newest developments for add-ons, techniques, optics and detectors, and even an up-grade option for future development concerning novel chopper approach (SPEED/Fourier) has been incorporated in the design. To address potential future scientific requirements, the design layout also allows addition of complementary diffraction capabilities.

ODIN will be able to deliver data from day one operation. It will outperform all existing facilities and allow for new methods with outstanding applications. ODIN allows combining direct imaging with un-polarized and polarized neutrons with reciprocal space techniques like diffraction and small angle scattering, and hence provides unprecedented capabilities for doing research in many areas of science and industry. In particular, the uniquely designed combination of a direct spatial resolution of micrometers and a reciprocal space resolution range in the micrometer to the nanometer regime provides a very powerful tool that is not available today. These length scales allow hydrogen detection and transport characterization with unprecedented precision, study of externally triggered transitions in soft matter and biology, development of materials for medical applications, and observation of structural changes in engineering materials during processes like in-situ observations of laser or steer welding. In addition, the application of polarized neutrons allows precision characterization of magnetic structures and processes critical for designing robust and high density data storage and magnetic levitation materials, study of phase transition in superconducting materials and devices, and industrial engineering of materials such as transformer steels with large magnetic domain structures. Finally yet importantly, all these capabilities also allow much enhanced non-destructive investigations of irreplaceable artifacts of art and cultural heritage thus providing a much needed capability to museums and conservation scientists to preserve and understand our shared human and planet history.

ODIN will meet future demands of a large and demanding user community in industrial research, applied sciences, and basic research for many years to come. It is likely to attract users from all over the world. It belongs to an instrument class that is already over-subscribed word wide. In view of the novel capabilities that ODIN will add to the current state-of-the-art, the likely over-subscription will be partially offset by faster measurement time, higher quality data, enhanced data reduction and analysis, and better infrastructural support for the user community. However, it is conceivable that at a later stage a second simpler complementary instrument may be needed for routine and long running conventional applications.

Work Units SD040ESS

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1. INSTRUMENT PROPOSAL

1.1 Scientific Impact

The impact of a neutron-imaging instrument is two-fold. There is an impact on services and applications for industry and then there is a broad field of scientific applications. ODIN with its outstanding and versatile capabilities will push the limits of current applications and will add many more. ODIN will significantly shift the boundaries of what can be done today. Simultaneous structural resolution, novel spatial resolved scattering modalities enabled by the unique and efficient pulsed beam approach, increased sensitivity for low Z element (such as hydrogen and lithium) detection 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. Following is a short and incomplete list of potential and cutting edge applications enabled by ODIN.

In energy research identification of clusters and agglomerations of hydrogen on the mesoscopic scale as well as deformations of hydrogen containing crystal lattices on the Angstrom scale (via Bragg edge imaging) will enable significant new insights in the processes of hydrogen uptake and release in materials. The understanding of these key phenomena is critical for designing hydrogen storage materials and devices, a crucial factor in enabling the hydrogen economy. In situ observation of battery charging and de-charging with chemical and structural sensitivity provided by Bragg edge observations will provide long desired ion transport insights that are critical for increased energy density and charge retention time for batteries and other energy storage devices. In addition, increased chemical sensitivity, spatial resolution, and efficiency will also add capability in important fields of research in catalysis, fuel cells, and nuclear energy materials.

Magnetism and hard matter research is a recent focus of neutron imaging. Polarized imaging and dark-field imaging have been used to locate and visualize inhomogeneity in magnetic fields and structures, magnetic phase transitions, and individual magnetic domains in bulk samples. Though nascent, this was very important and pioneering research, and demonstrated the potential of neutron imaging in the study of magnetic materials. ODIN will allow for more efficient and precise measurements enabling full characterization of domain structures in three dimensions providing invaluable insights in structure and behavior of these materials. This information is essential for developing high-density data storage materials, and for energy efficient magnetic materials in engineering applications. Time resolved studies of phase transitions of these materials could be envisaged as well as the exploitation of their sensitivity to the magnetic fields of electrical currents. Finally, phenomena of superconductivity can be investigated in a wide range of length scales simultaneously. Such investigation is indispensable for the characterization of the arrangement of vortices, an essential step for the design of superconductive devices.

Engineering materials display a broad range of issues addressed best by neutrons and ODIN will enable highly effective approaches to study strains, textures, and microstructures deep in metal components allowing investigation of crucial processes such as crack growth, and its relation to individual grains, and their assembly and orientation. ODIN will be outstanding for such observations in order to predict and prevent material failures.

Additionally, in-situ mapping of strains, texture, and porosity in materials subjected to processes such as applied load, varying environmental and production conditions, hydrogen content variation, and welding can be carried out. These processes play important roles in the determination of integrity of materials and their reliable performance. Material behavior under such processes will be one of the primary focuses of ODIN and will provide better measurement capabilities than any other existing imaging instrument.

Geology, earth and agricultural sciences already utilize neutron imaging and will profit from extended information in data collected at ODIN that will reveal enhanced structural details on various length scales in materials like rocks, sands and soil even under extreme conditions. Enhanced structural details will also be obtained from in-situ experiments involving strain, high pressure, and water content and distribution. This structural information is very often the key to the understanding and the ability to distinguish different length scale processes ranging from water economy at the interface of soil and roots, water transport mechanism in ground fractures, compaction and movement of sandy grounds, and soil transport characteristics in large scale of earthquakes and continental shifts. Application in the determination of porosity and void fraction in rocks is relevant for the environmentally important study of CO_2 stored in the ground and the exploitation of natural resources like oil and gas, all of which require knowledge of structural composition of the surrounding grounds.

Soft matter and biology will utilize ODIN’s capability to obtain spatially resolved SANS information in the dark-field mode and will open doors for neutron imaging into the world of micro- and nanostructures. While neutron imaging in biology is capable of in-vivo measurements, the current investigations are limited to large-scale biological structures and objects, such as water content and water uptake of plants and fruits on the macroscopic scale. ODIN will allow for simultaneous views onto microstructural details and transitions in biology along with soft matter investigations and externally triggered transitions in soft matter. Structural effects like self-assembly phenomena under locally varying conditions such as shear will be a focus of research. A fundamental understanding of resulting effects is indispensable for an insight into the biophysical processes of life. Such understanding is also important for technological advancement in the development of key medical materials such as Myelin and other multi-scale structures. In addition, given the capabilities of ODIN, biopsies of human tissue can be a potentially attractive field of application as well.

Archeology, Paleontology, and Cultural heritage research already successfully uses neutron imaging at various facilities. ODIN will enhance the current research capability by providing significantly more information about the structure and microstructure of irreplaceable artifacts that includes ancient tools and weapons, fossils and artworks. Better resolution and the ability of ODIN to map microstructures will provide information not available by other non-invasive techniques. This in turn will allow for better understanding of the origin of such artifacts, ancient metallurgy and fabrication techniques, cultural and social motivations, prevailing environment condition etc. in order to provide a more complete image of the past of the human kind, life on our planet, and the planet itself.

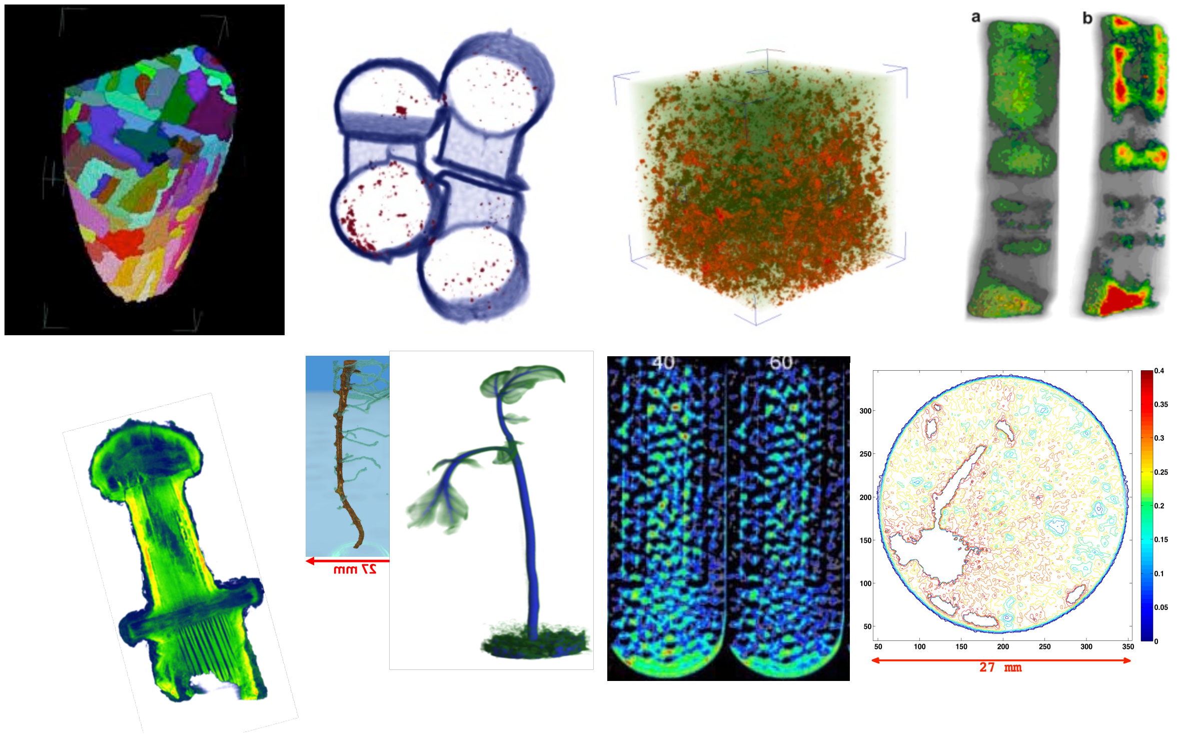


Fig. 1 scientific applications (from left to right) top: first visualization of magnetic domains (HZB), porosity distribution in casted Al specimen (HZB), crystalline phase distribution in martensitic steel sample (HZB), 3D Curie temperature map in NiPd crystal (HZB, TUM), sword artifact (HZB), plant root (PSI) and tomato seedling (HZB) from water uptake studies, hydrogen storage investigations (NIST), water distribution in soil around plant roots (PSI);

Alternative Energy and Environment research in fuel cell and battery studies in conjunction with **commercial product development** have developed into a central field of application for neutron imaging. Within the last decade an industry financed imaging beam line has been developed and has been in operation at NIST, USA, primarily to address this specific field of research. Improved resolution as well as the structural and (indirect) chemical sensitivity due to Bragg edge information provided by ODIN will have a major impact in observing exchange processes in Proton Exchange Membrane Fuel Cells (PEMFCs) but also for example the integrity of Solid Oxide Fuel Cells (SOFCs). However, other efforts towards more environmental friendly products, like the R&D of diesel particulate filter, also rely on neutron imaging and will profit significantly form the novel capabilities and efficiency of ODIN. In this field the aerospace and automotive industry are important customers and stakeholders and this is likely to be the case for the foreseeable future. ODIN will make special efforts to attract these important stakeholders.

Routine Non-Destructive Evaluation of Material Reliability is a critical factor in industrial productions. Neutron imaging is very often the only and the most successful tool to identify and investigate component failures non-destructively. The neutron metallurgical studies of the ocean liner 'Titanic' rivets and the metal structures of the 'Twin Towers' in New York are famous examples. However, numerous industrial processes use neutrons for pre- and post-construction reliability tests. With the enhanced capabilities of ODIN, neutron imaging has immense potential to compete with any other neutron or x-ray technique for these applications. The list of applications is endless and the main limitation is mostly the lack of awareness in industry of the availability and capability of the neutron imaging method, that requires adequate outreach activities (activities of the imaging group at PSI can be a guide) to rectify. It has been shown in the past that many even conventional applications can profit from higher energy resolution to increase sensitivity or to identify relevant microstructural features such as porosity and voids. With orders of magnitude better energy resolution and time of flight (TOF) imaging methods ODIN will be highly efficient in detecting stress and strain distributions and microstructural inhomogeneity that contribute to structural failure in materials but can also help to engineer better material products and develop construction processes such as welding. The development of exotic materials such as transformer steel with big magnetic domains is important for industry. Effective non-destructive evaluation of production material in a facility like ODIN will be a crucial factor in the introduction of these materials in commercial products.

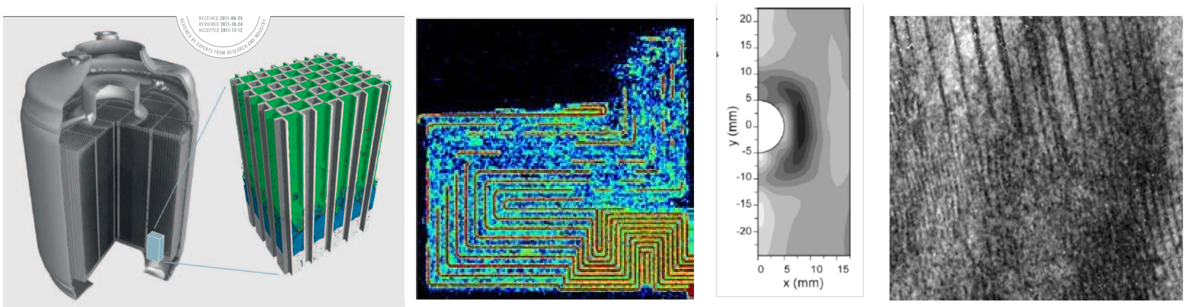


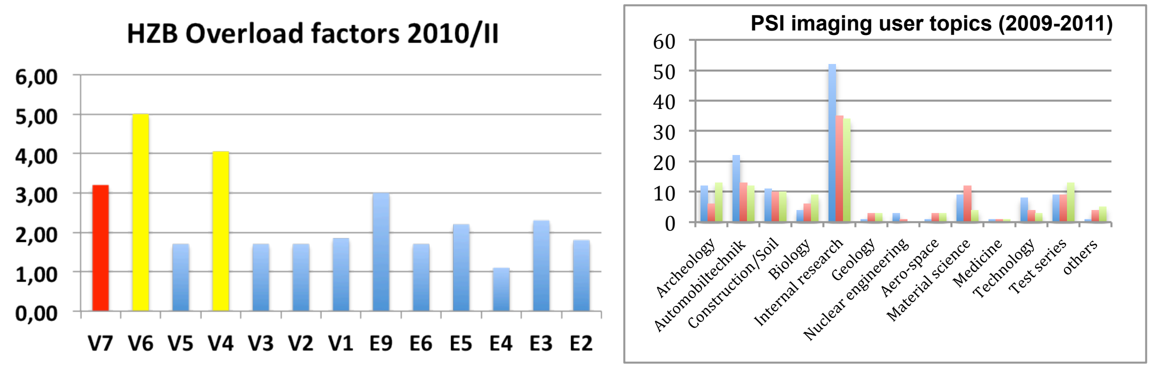
Fig. 2 Industrial applications (from left to right) diesel particulate filter (PSI), water distribution in operating fuel cell (NIST), strain map around a drilled whole in steel (ISIS), magnetic domains in transformer steel (HZB)

A complete list and description of all current and potential future scientific and industrial applications is beyond the scope of this document. However, neutron imaging is a robust and perhaps the fastest growing field in neutron science. The pulsed beam instrument ODIN will offer the widest variety of methods with unmatched capabilities and efficiency that will open up new research frontiers. The future of neutron imaging is bright and ODIN will play a central and leading role catering to a wide variety of stakeholders from industry to academia.

1.2 User Base and Demand

The prediction of the user base has certainly to be based on the past user records of existing facilities first. For that reason we have collected corresponding information from the leading imaging facilities in Europe (HZB, PSI, TUM) and the US (NIST).

These statistics show that the existing world class facilities have a growing user demand and overload factors at all these instruments are higher than two on a regular basis. At CONRAD at HZB the **overload factor sometimes exceeds 3** and is the **third highest** ranging (Fig. 3, left) only slightly behind the SANS instrument and the neutron reflectometer, both of which have recently doubled their capacity by installing one more instrument of that class.



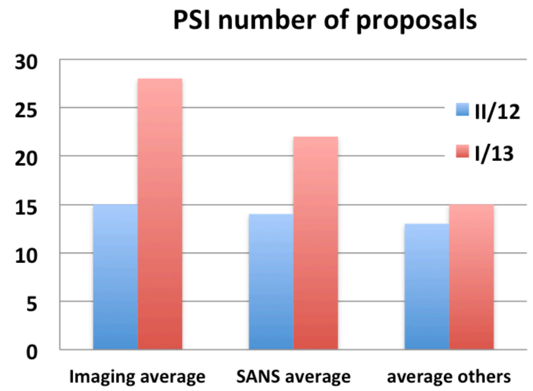


Fig. 3 left top: HZB overload factors 2010/II (V7 imaging, note: yellow are SANS and reflectometer, both of which had a second instrument under construction at that time); right top: PSI imaging users in different fields of applications. Left: PSI statistics on number of proposals for the last two cycles, note that PSI has two imaging stations; (data courtesy PSI and HZB imaging groups and user offices)

The **ratio of academic to industrial** user demand ranges at about 2:1 (PSI, NIST) already now, where mainly conventional imaging is applied. In this context internally triggered research and instrument development, within the corresponding institution or bigger organization ranges up to 1/3 of the beamtime.

Another important aspect is the **local outreach**, especially in certain fields of applications like **industrial and cultural heritage** but also other scientific fields not too familiar with large scale research facilities. They are responsible for a partly very locally concentrated user community (besides in-house research), like for example represented in the imaging user statistics of PSI specifying the countries where users come from (Fig. 4 left).

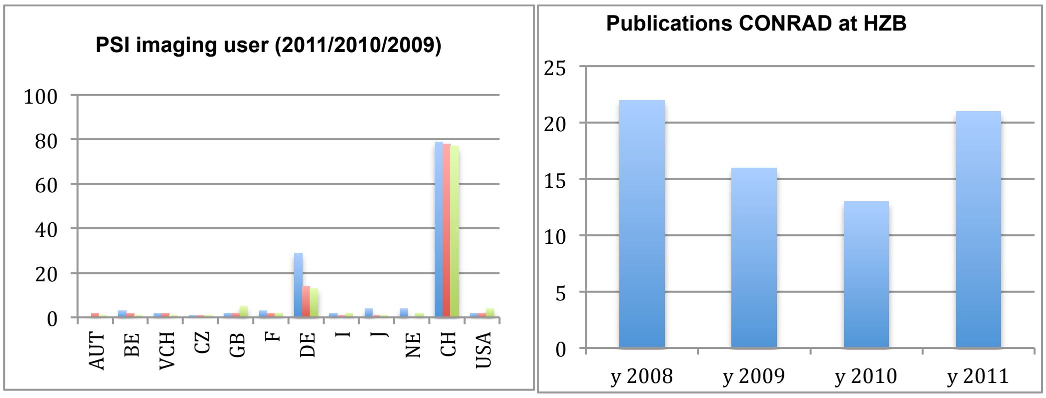


Fig. 4 Imaging users at PSI from corresponding countries of origin (left) and publication statistics of CONRAD at HZB (right)

This last fact underlines two issues:

1. the **local** availability of a neutron imaging facility is very important and serves very much a local community and industry. In turn that means that the concurrency between facilities in certain user communities of the instrument is relatively low. Therefore also conventional imaging, where the ESS instrument does not necessarily outperform but more likely equals instruments at state of the art high flux sources is essential for the community and the local community in particular.

2. a corresponding **outreach and information policy** concerning the capabilities of an imaging instrument are key for building up a user community and serving industry and society to the best possible extend.

In summary, neutron imaging has a **very strong and still fast growing user community** both in industry and science, even when taking into account only conventional applications and methods. It can be predicted, that the availability of novel imaging modalities with highest efficiency as implemented in the ODIN concept, will have a huge impact on the capability and request of imaging at ESS. On the long run that might and will even mean that **a second imaging station** mainly serving conventional applications and industry has to be taken into account.

As imaging serves also **industrial applications and propriety research** not all experiments and especially industrial applications produce scientific publication. Therefore, and because very important applications solving severe problems in a specific field or industrial process do not produce a significant scientific impact, the impact of neutron imaging can not solely be measured by scientific means and publication output. Nevertheless the publication statistics of neutron imaging as presented above (Fig. 4, right) and below are impressive and do not fall behind other leading neutron instrumentation. Additionally, neutron imaging instruments have a financial impact when serving industry and receiving payments for propriety research and measurements. At many institutions this income covers a large amount of the cost of the instrument and enables significant industrial outreach programs. At PSI for example industrial income constantly covers 3 scientist positions, while at NIST a significant percentage of the operation cost is carried by industry.

The **number of publications per year** ranges between 12 and 25 per imaging station at the leading instruments on top of industrial applications and like reported by the NIST imaging facility 2 patents per year (5 year statistic). The HZB Conrad instrument (note an instrument at a medium flux source) has had 21 publications in 2011, among which there are 8 with impact factors bigger than 3 and 3 above 5.

1.3 Description of Instrument Concept and Performance

1.3.1. Definition of scope and requirements

To serve the science drivers and take maximum advantage of the source characteristics the instrument is to be designed such, that it enables time-of-flight methods in imaging [1-11] with maximum flexibility and efficiency, while not compromising a sufficient size and homogeneity of the field of view (FOV) also for conventional white beam imaging [12,13] profiting from the world leading time averaged flux of ESS. An overview of the corresponding requirements of the instrument to enable these goals, which defined the scope of the instrument concept and specification, can be found in Table 1.

method/ application	wavelength band	wavelength resolution	max. FOV	max spatial resolution
Bragg edge/ strain mapping	1Å-5.5Å	0.3%	100x100mm2	<0.2mm
Bragg edge texture	1Å-5.5Å	1%	100x100mm2	<0.01mm
Bragg edge/ microstructure	2Å-6Å	10%	100x100mm2	<0.01mm
polarized neutrons/ magnetic phenomena	1Å-10(20)Å	1%	100x100mm2	<0.05mm
Dark-field contrast/ 2D SANS mapping	2Å-10(20)Å	10%	100x100mm2	<0.05mm
convetional imaging/ macroscop. structure	monochrom/cold thermal/bi-spec	10%/-/-/-	250x250 mm2	<0.001mm

Table 1 Instrumental requirements for the realization and efficient application of different modalities needed with respect to the defined science case and in order to take full advantage of the source characteristics for neutron imaging (note: parameters for FOV and spatial resolution are currently considered maximum requirements, which are currently not necessarily used or considered in combination).

1.3.2. Concept

The basic concept to meet the defined requirements is already outlined in [10,11]. The length of the instrument is accordingly chosen with 60 m such that the lowest required TOF resolution is achieved for 2Å at that length given the source pulse length of 2.86 ms. At that length the corresponding wavelength range also matches with a width of 4.6Å the most basic range required. It can however be also extended to multiples of that value by pulse suppression in order to cover a more sufficient range for some cases like e.g. time and spatial resolved studies involving small angle scattering. In order to achieve better TOF resolutions, required for example for many Bragg edge studies [1-11], a wavelength frame multiplication (WFM) [10,14,15] chopper system is foreseen (Fig. 5). This system is based on a moveable pair of optical blind [15,16,17] pulse shaping choppers (potentially both double choppers) for constant wavelength resolution. At the long pulse source they are combined with WFM (associated with a number of sub-frame overlap choppers, i.e. three to six double choppers) (Fig. 5). Changing the distance between the pulse shaping choppers allows for tuning the resolution. The whole system works for every pulse and for a single pulse suppression mode (requires wavelength band chopper(s)) in order to cover different required wavelength bands simultaneously. In order to tune to high resolutions the beam cross section at the pulse shaping choppers just outside the target monolith has to be limited [15]. Therefore an eye-of-the-needle approach, where the beam is focused between these two choppers is foreseen. This focus spot can be seen as a virtual source from which the neutrons have to be picked up and refocused into the pinhole of a conventional pinhole geometry for neutron imaging at 50 m from the moderator followed by an up to 10 m long flight path in front of the detector position (Fig. 6). This allows for achieving the maximum desired FOV in a comparable manner to a standard approach at continuous sources where the pinhole would be already in the first focal spot. Additionally, the instrument has to take advantage of the bi-spectral extraction opportunity at ESS in order to satisfy the wavelength band requirements ranging from 1Å (e.g. Bragg edge strain mapping [1-11]) to well above 10Å (e.g. mapping of small angle scattering [18-22]).

On the basis of this principal concept [10,11] the ODIN beamline is to be specified in detail, which will be described in the following paragraphs.

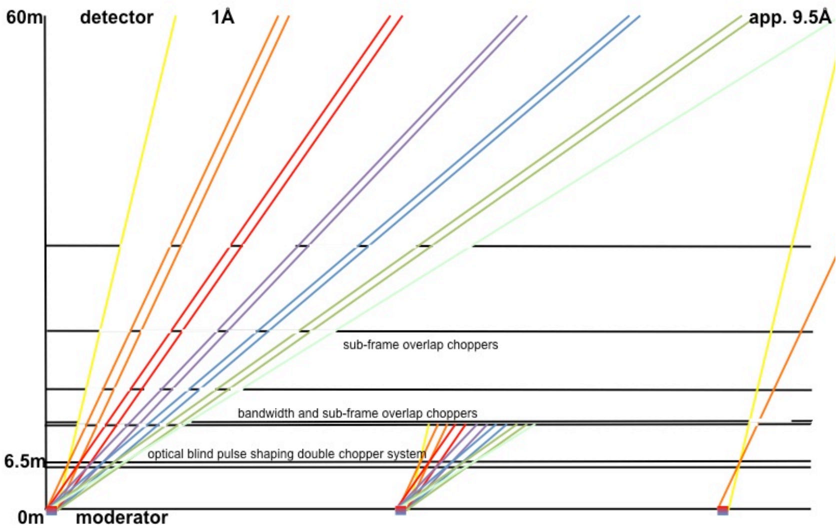


Fig. 5 Basic idea of chopper set-up (here with one fold pulse suppression and WFM in operation)(compare [8,15])

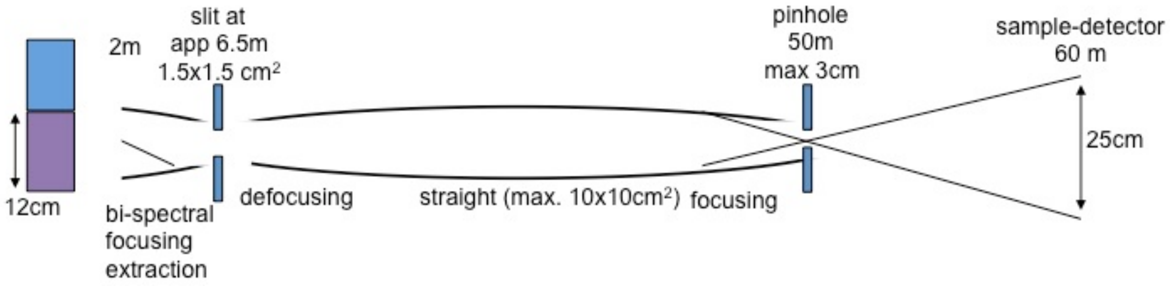


Fig. 6 Basic idea of ODIN guide system [11]

1.3.3. Specification

This section provides preliminary specification and descriptions of all major components of the instrument and their functionality based on simulations and analytical considerations. In some cases also alternative solutions have been taken into account, especially when the preferred solution has been judged to bare significant (technological) risk. These risks and alternative solutions including potential tradeoffs will be discussed in the corresponding section 3.5.

1.3.3.1. Bi-spectral extraction

The bi-spectral extraction approach is based on the availability of a cold and thermal moderator at ESS like outlined in the ESS baseline. These moderator surfaces will be located side by side and hence the cold spectrum can be deflected in the horizontal plane into an extraction guide pointing to the thermal moderator surface. The bi-spectral extraction (Fig. 7) was optimized [23] to consist of three bent mirrors positioned vertically in the beam from 2 m to 3 m from the moderator. Their angle to the axis of the subsequent parabolic focusing section from 3 to 6.45 m from the moderator (note: this focusing extraction part is 0.45 m longer than in the corresponding publication [23], which can only have a positive impact on the performance of this section) gradually changes from 1.4 deg to 1 deg on their length of 1 m. The parabolic section starts at 3 m and 2 m from the source on the side of the cold moderator and the opposite side, respectively. It was found that the weight of efficiency between the cold moderator and thermal moderator spectra transported can be shifted by shifting the in-pile axis parallel further to the cold or more to the centre of the thermal moderator. In the moment the central position is favored due to a slightly higher and more homogeneous flux at the detector (Fig. 8). That puts stronger weight on the thermal part (10% less cold flux), but fine-tuning and a final choice can still be made (Fig. 8).

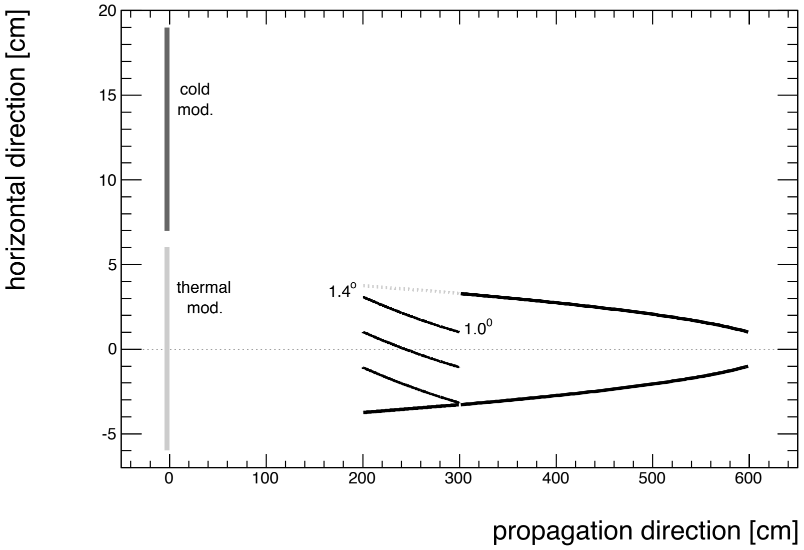


Fig. 7 Sketch horizontal plane of extraction system [23]

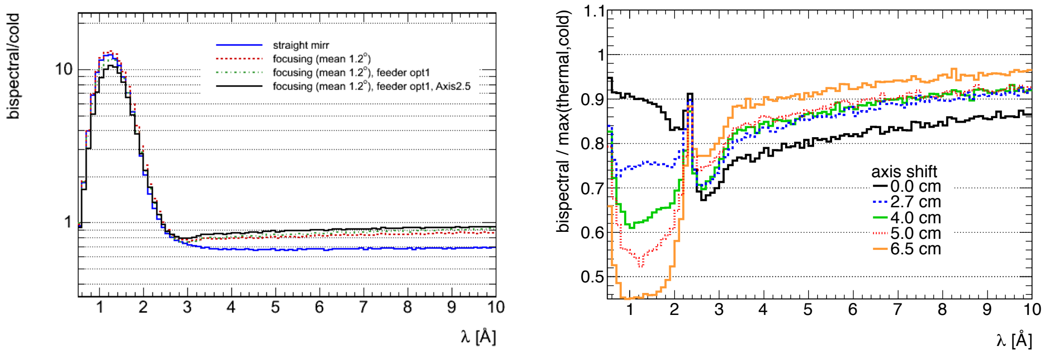


Fig. 8 Performance of different bi-spectral extraction geometries compared to cold spectrum and efficiency for different guide axis positions (relative to thermal moderator centre) [23]

1.3.3.2. Neutron guide system

Geometry

The neutron guide system (Fig. 6), which has been optimized by simulations, starts at 2 m from the moderator with the bi-spectral extraction system and focuses into the eye of the needle position between the two identical pulse shaping choppers, i.e. at 6.75 m. This extraction section of the guide ends at 6.45 m from the moderator at the outermost position of the first pulse shaping chopper (see corresponding section). The beam is focused to 1.5x1.5 cm^2 in order to allow for the chopping accuracy required to achieve the highest targeted wavelength resolution. From this focal spot a long guide system transfers neutrons to the variable pinhole of the imaging set-up in the endstation.

In order to transfer the neutrons efficiently an elliptical defocussing section is foreseen after the first focal spot starting at 7.05 m and extending to 17.05m from the moderator.

It is followed by a 19.5m long (straight) section with a cross section of 9.6x9.6 cm^2, which is a consequence of limiting the guide cross section to a maximum of 10x10cm^2 before starting guide optimization simulations due to the requirements for chopping the beam with sufficient accuracy.

Finally another elliptical focusing section ending at 48.5 m is focusing the beam into the (variable) pinhole at the 50 m position. The standard pinhole has a diameter of 3 cm, whereas for smaller pinholes used, variable focusing guide extensions are considered.

The guides are coated with different m values from a maximum of m=6 in the outermost parts of the focusing sections to a minimum of m=2 in the central region of the constant section. A detailed optimization with respect to cost, however, has to still be performed.

Neutron transport

The transported neutron flux has been benchmarked with a considered conventional pin-hole imaging instrument geometry featuring a 3 cm pinhole at the 6.75 m position followed by a 10 m flight path analogue to the ODIN setup at 50-60m. Such set-up has been simulated to provide a cold neutron flux comparable with or outperforming the currently highest flux imaging station ANTARES at TUM [24], depending whether the old or new definition of the cold moderator of ESS is used.

It is found that the optimized guide system viewing the cold moderator only would sacrifice about 40-45% of the flux on a FOV of 20x20 cm^2 at the sample-detector position as compared to the benchmark. However, the bi-spectral extraction compensates for these losses and provides an integral flux density comparable to that of the benchmark instrument (Fig.8, right side). Here it shall be noted, that the 0.6m long guide interruption between 6.45 and 7.05m has no significant impact on the neutron transport as the transported neutrons are focused there. Hence, ODIN will outperform the world leading imaging instruments even in terms of time integrated flux, remarkably some of the most productive state-of-the-art instruments in Europe at PSI [25] and HZB [26] even by more than an order of magnitude.

Spatial beam homogeneity

However, not only the flux density but especially also the homogeneity of the flux distribution on the FOV of the imaging detector is a significant quality factor for an imaging instrument. Naturally guides and especially also focusing sections introduce inhomogeneities in the transported divergence, which is aimed to be as large as possible for an imaging instrument in order to achieve a large FOV even after pinholes of small sizes. An imhomogeneous divergence translates directly into spatial inhomogeneities projected through the pinhole onto the imaging detector. Smooth inhomogeneities can easily be corrected by data treatment, however, the lower flux in some regions also rules the statistics achieved.

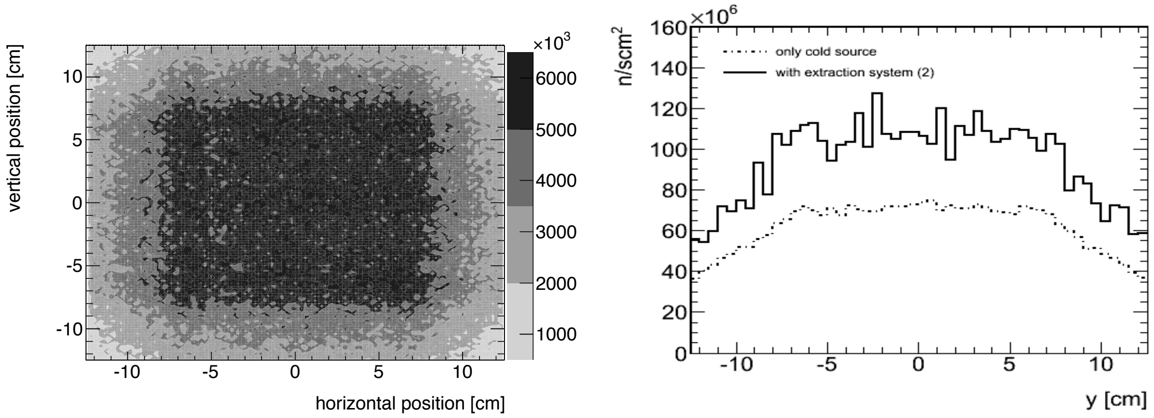


Fig. 9 Example of beam cross section as simulated on the detector as well as a corresponding horizontal flux density profile with and without taking into account the bi-spectral extraction[23]

The achieved spatial homogeneity (Fig. 9), which is however dependent on the collimation, i.e. the used pinhole size and pinhole to detector distance, is comparable to what is found in other state-of-the-art imaging instruments performing extremely well at neutron guides, e.g. CONRAD at HZB [26]. More extreme inhomogeneities in case very small pinholes are used can be smoothened sufficiently by the use of graphite diffusers in the pinhole region implying only minor flux losses of the order of a few percent.

Spectral beam homogeneity

Another important issue is the homogeneity of the spectral distribution over the FOV as it might have significant impact on the correct quantification of measurements, while guides are well known to introduce inhomogeneities corresponding to the wavelength dependence of the total reflection angle. Although at a pulsed source the spectrum contributing in each pixel of an imaging detector can be measured easily and hence corresponding corrections can be made, also this aspect has been investigated carefully (Fig. 10).

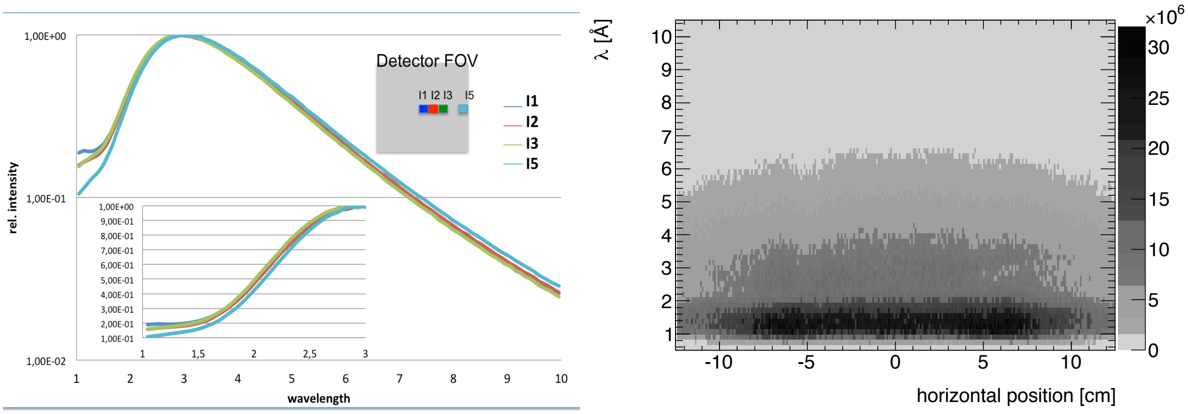


Fig. 10 normalized spectra at different regions of interest from the centre to the side of the FOV highlighting the short wavelength side in an insert (left) and the spectral distribution along the horizontal axis of the FOV (right)

However, it can be seen from Fig. xx that the spectral homogeneity is excellent even for short wavelengths (down to 1Å) for the inner 15x15 cm^2 of the FOV. Only in the outmost 5 cm of the field of view slight deviations are found below 2Å and above about 6 Å. These however are not significant to the performance of the instrument.

Additional guide consideration

In addition several approaches to loose direct line of sight onto the moderator have been and are under investigation for in case such option becomes favorable due to yet unknown boundary conditions concerning prompt pulse and background considerations. More details are given in the risk section of this proposal. However, these involve additional transport losses and inhomogneities to be considered carefully.

1.3.3.3. Prompt pulse suppression – T0 chopper

In order to suppress the prompt pulse despite the favored straight guide geometry a T0 approach was chosen. The T0 chopper will be positioned starting at 9 m and will have a length of 0.5 m along which the guide system is interrupted. The position of the chopper at 9-9.5 m was chosen such, that at this place the shortest wavelength utilized (1Å) has separated from the prompt pulse sufficiently to allow also for opening and closing of the T0 chopper without interfering with the 1Å neutrons. The positioning also takes into account that the hammer should not interfere with the longest desired wavelengths even in pulse suppression mode. Comparable solutions can be found at JPARC beamlines [27,28] (Fig. 11), most notably it is foreseen for the imaging beamline ibid involving a T0 chopper of similar momentum. The considerations are, however, based on the assumption that a comparable length of the hammer like at JPARC is sufficient at ESS, with the only difference that the prompt pulse is longer and hence the hammer needs to close longer. (Note that corresponding numbers and facts for ESS are still missing, but will be available on time for a final choice.) The associated bigger size and weight is somewhat counterbalanced by a lower rotation frequency of 28 Hz, i.e. 2 times the source frequency. The corresponding risks and successful mitigation are discussed in the corresponding section. The summarized specifications of the T0 chopper are:

T0 chopper: 50 cm thickness (material compare JPARC choppers or further optimized)

diameter 70 cm, full closing time 2.9 ms, app. 43 deg hammer size, frequency 28 Hz

Fig. 11 T0 chopper at JPARC [27]

1.3.3.4. Chopper system

The required chopper system to provide all the functionality described above and in detail in section 1.3.4 conveys besides the T0 chopper 2 pulse shaping choppers (PSC), at least one band width chopper (BWC) (i.e. wavelength band and pulse suppression chopper) and several sub-frame overlap choppers (FOC). All these choppers are disc choppers, mostly double-disc choppers. The band width choppers (BWC) allow for adapting the frame size to the desired wavelength frame to be utilized in a measurement, while their frequency allows for suppressing pulses when required. The FOC have to be considered counter rotating double disc choppers in order to improve the opening and closing behavior of the choppers as compared to single discs. This is required as they operate at relatively big guide cross sections at low speeds and require sharp and partly very short closing times in order to well separate sub-frames without interfering with their overlap in terms of wavelengths.

The TOF resolution can be changed by moving the PSCs towards each other from 50 cm to 12 cm, which in principle enables the desired constant wavelength resolutions from 1% to a minimum of 0.3%. Therefore they have to be placed on linear translation stages [17] (Fig. 12). Despite the relatively small cross section in the eye of the needle focus spot it can be calculated [16] that single chopper discs are not sufficient to provide the nominal resolutions envisaged at the limited feasible chopper speeds. Chopper speeds are limited to 4 times the source frequency (56 Hz) due to the required 6 individually sized windows for such optical blind WFM system [15]. Consequently, maximum performance requires each of these pulse shaping choppers to be designed as a counter rotating double disc chopper. A potential corresponding design is sketched in Fig. 12.

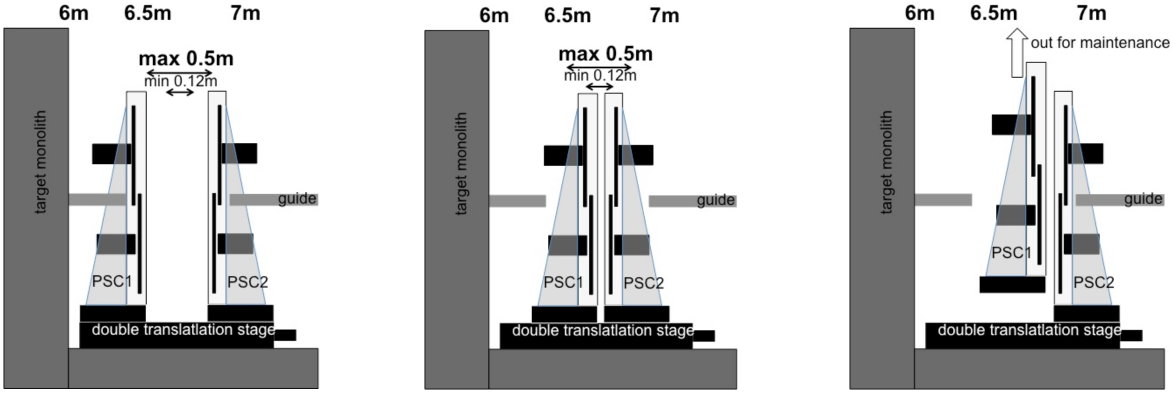
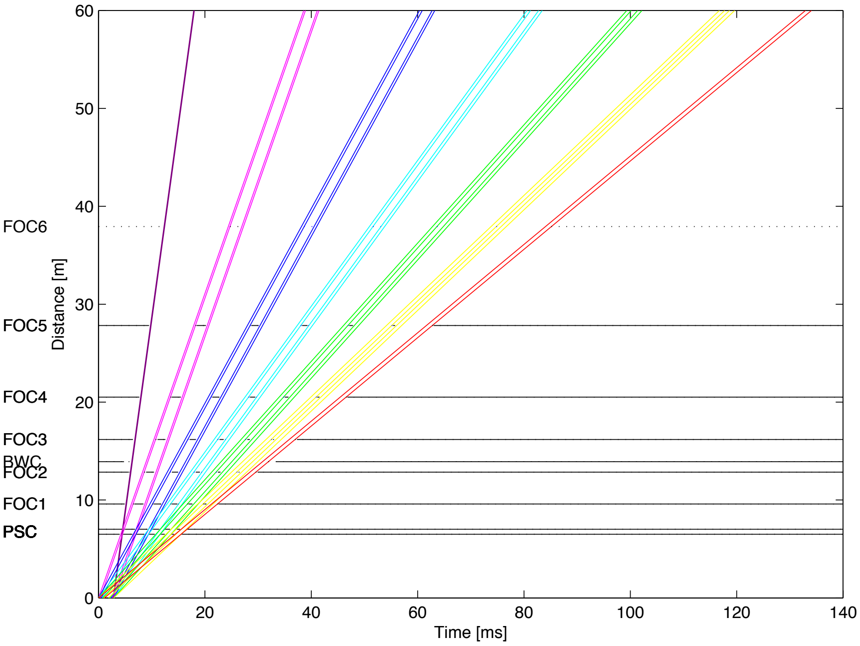


Fig. 12 Potential layout of optical blind double chopper system consisting of two double disc choppers. Left displays the minimum resolution mode and the sketch in the middle the maximum resolution mode, while the right sketch illustrates the considered solution for a maintenance case that requires removal of the chopper.

As in such set-up choppers have to be set facing each other, the chopper support allows the first chopper disc not at 6m but it has been foreseen at 6.5 m (compare Fig. 12). This allows for neighboring beamlines to set there choppers at the monolith wall at 6m potentially. However, it also implies that a solution with several choppers fixed in position instead of the movable ones to realize different resolutions must seem not feasible as that distance of 0.5m is too short and the range of resolutions would be limited and potentially causing severe sacrifice in performance. Such solution would also exclude magnetic bearings.

On the basis of these boundary conditions the chopper system has been specified analytically with a correspondingly developed program [L. Udby, M. Strobl, to be published] that allows for fast adaptation in case single boundary conditions will still change due to engineering design requirements. The program is based on the concept and method of TOF diagrams [Fig. 13] like introduced in [15] and takes chopper opening and closing times (radius, frequency, guide cross section) into account.



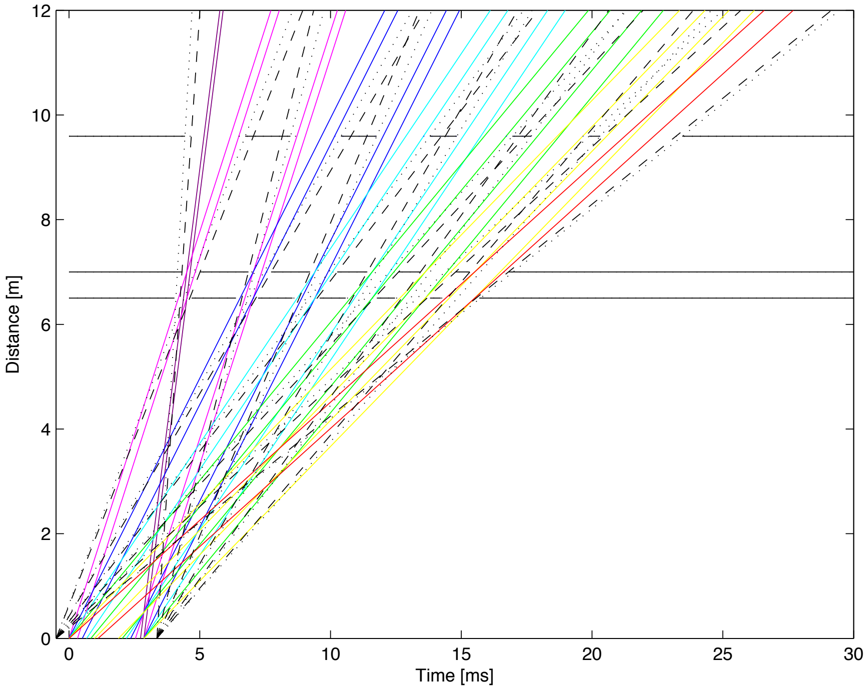


Fig. 13 Time-of-flight diagram as derived from specification program for 1% wavelength resolution and single pulse suppression mode (top) and a corresponding detail of the first 12 m indicating potential overlapping trajectories to be eliminated.

This way the chopper system has been specified to the values given in Table 2, which have subsequently been verified by simulations for all foreseen operation modes. Examples of the spectral performance of the single pulse suppression mode are given in Fig. 14. They prove the validity of the specification as well as that sufficient overlap can be achieved in the wavelength domain while sufficient separation is given in the TOF flight domain. Further they show that the flux density scales well with the resolution, i.e. that no significant losses are induced by the WFM approach.

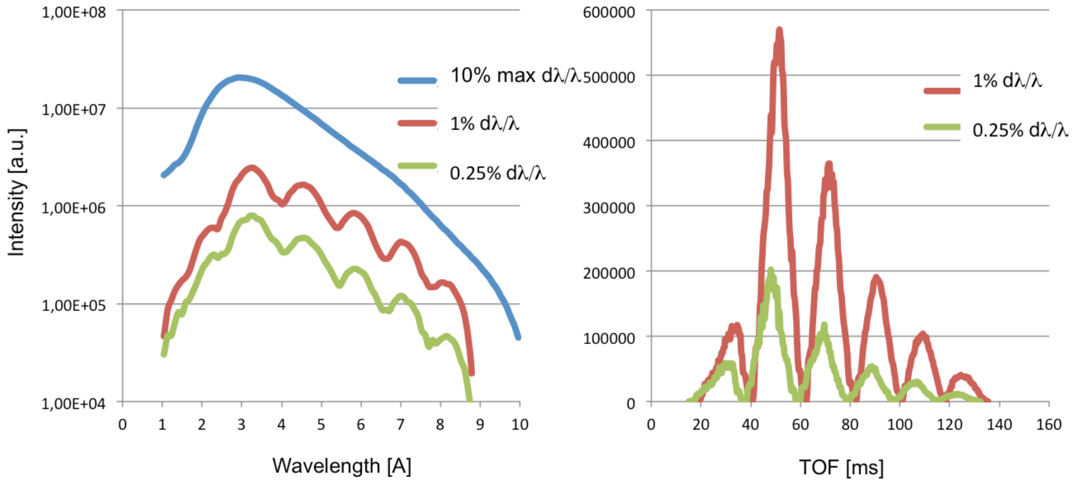


Fig. 14 Results of simulations verifying the performance of the chopper system as specified

The diameters and the choice of frequencies to be set of the choppers are diverse. While the PSCs have a diameter of 70 cm (housings maximum 80cm width) in order to fit with 5 deg neighboring beamlines at 6-7 m, other choppers, in particular FOCs located around half length of the instrument are running consequently at lower frequencies and have more space. Therefore they are bigger and for now their maximum diameter is fixed to 2m, which still seems feasible and not to far from known solutions. (however, note: they are dominated by windows; 6 windows with sizes between 20 and over 40 degree). All choppers are double disc choppers in order to minimize opening and closing times. A preliminary overview is provided in the following Table. 2.

	frame 1	frame2	frame3	frame4	frame5	frame6	radius	frequency	position
	[deg]	[deg]	[deg]	[deg]	[deg]	[deg]	[m]	[Hz]	[m]
PSC1	6,48	10,14	13,53	16,68	19,61	22,33	0,35	56,00	6,5 (6.7)
PSC2	6,48	10,14	13,53	16,68	19,61	22,33	0,35	56,00	7 (6,8)
FOC1	20,18	21,83	23,36	24,78	26,10	27,32	0,35	42,00	9,59
FOC2	26,24	26,43	26,60	26,76	26,91	27,04	0,35	28,00	12,84
BWC	64,64						0,02	7 (14)	13
FOC3	39,38	38,62	37,92	37,27	36,67	36,11	0,35	28,00	16,18
FOC4	28,21	27,23	26,31	25,46	24,67	23,94	1,00	14,00	20,51
FOC5	42,61	40,60	38,73	37,00	35,38	33,88	1,00	14,00	27,83
FOC6	31,25	29,53	27,94	26,46	25,08	23,80	1,00	7,00	37,93

Table 2 Main chopper parameters. Note that chopper FOC6 (grey) is only operated in pulse suppression mode, but not required if only the first 3 frames are utilized, i.e. when all source pulses are contributing.

1.3.3.5. Shutters

The requirements for shutters depend on the gamma and fast neutron background that has to be expected. No sufficient calculations and numbers on that could be provided from the corresponding groups in ESS yet. However, several solutions have been taken into account that can be realized depending on these data. The following considerations have been made in order to enable access to the sample position and potentially components further upstream for maintenance during source operation despite direct line of site.

I. The T0 chopper potentially blocks the gamma and fast neutrons sufficiently for measurements, hence the remaining thermal and cold neutron beam should be attenuated sufficiently for access by a light shutter, that can be placed at the pinhole position. (Here the eye of the needle and the relatively long beamline are in favor a lower background.) However, as that does not satisfy safety requirements as the T0 chopper could fail the light shutter foreseen in the target monolith baseline has to be shut in such case as well. This shutter has the same dimension as the T0 chopper. Together they can potentially even be considered as a heavy shutter.

II. In case the light shutter (respectively the dimension of the T0 chopper) are not sufficient for safety, the T0 chopper can be foreseen to be movable in height so that blockage of the beam in any operation state of the chopper is ensured.

III. In case solution II is not sufficient either and to increase flexibility of access a (fail-safe) heavy shutter can be foreseen in the 1m region between the end of the guide and the pinhole, where in general heavy shielding according to the tapered dimensions of the beam should be in place.

IV. Again in case solution II does not proof sufficient for access to components downstream the T0 chopper a shutter along the guide just upstream or downstream the T0 position can be foreseen. Just like the light shutter such solution would require the shutter in open position to host the corresponding guide section of up to 1m and sufficient reproducibility needs to be guaranteed. This would in principle allow for accessing all components downstream this shutter, i.e. potentially including the T0 chopper during source operation.

1.3.3.6. Endstation

The endstation will be a massive concrete construction (comparable to that of IKON/PSI [25] Fig. 15) and will host at least two flexible sample-detector positions, more likely even a more flexible set-up allowing for more positions. A modular flight tube that includes fixed and adaptable beam limiters (slits) and might be evacuated (or He filled) will be installed. The endstation starts at the pin-hole position at 50 m has an inner length of up to 14 m and a width of at least 6 m (4 m and 2 m from beam axis). The height has still to be considered carefully also in terms of hall height and crane access for heavy and bulk samples and sample environment. Safety controlled access to the endstation is provided from the side such that no line of sight is provided between inside and outside. Supply and exhaust systems as well as safety requirements for valuable and activated objects do not need not be defined in detail yet, but are considered and will be taken care of continuously. This also applies for required infrastructure around the endstation and access to the hall in the vicinity of the endstation (truck access, cranes, safety storage, labs) as outlined below.

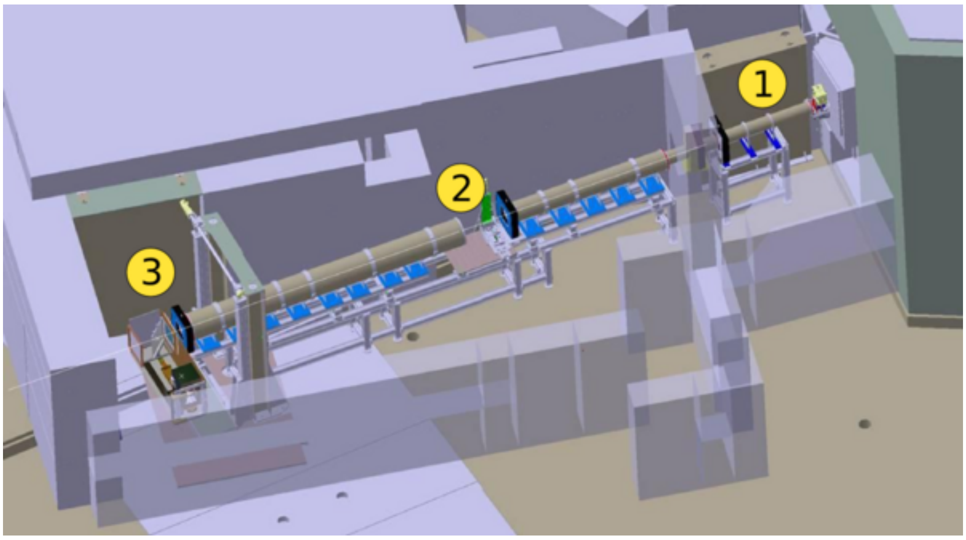


Fig. 15 Example of endstation of ICON imaging station at PSI (CH)[25]. Although installations in the endstation bunker of ODIN might look similar it is planned to provide significantly more space, in

order to have room for eventual diffraction detectors i.e. upgradeable detector coverage for complimentary diffraction studies (see below). A flexible setup is required to host all add-ons.

Pinhole geometry (for spatial resolution capability)
Within the endstation the potential spatial resolution and the FOV as defined by the geometry of such imaging set-up can be regulated and tailored to the requirements by different pinhole sizes D (at 50 m, free choice from 0 to 3 cm) and pinhole-to-detector distances L (0 to 13 m) defining the collimation ration L/D (form values of 30 to >3000) and consequently the image blur d limiting the spatial resolution ($d=l*D/L$, where l is the sample-detector distance)[12,13]. The variable pinhole set-up has still to be defined depending on background calculations at the pinhole position and might require a heavy rotary pinhole exchange system comparable to such in the biological shielding of reactor based imaging facilities or a variable slit sufficient for cold and thermal neutrons like at imaging instruments at neutron guide end positions.

Supply requirements
Experience at existing imaging beamlines imply that e.g. the following media supplies are required within the endstation (best in two separate positions): D_2, H_2 (requires safety system and sensors), vacuum, exhaust, He (in/out), N, pressured air, water (in/out) etc.;

Access requirements
Access to the hall in the vicinity of the instrument hutch and cabin is required for large objects (best truck access); crane access to hall entrance and endstation for heavy and bulk samples as well as sample environment; crane access through the roof of the endstation needs to be considered (in connection with endstation height); Safe rooms with limited access rights for storage of valuable objects and propriety research issues have to be available in the vicinity of the instrument (separate and limited access to the instrument area has to be considered for these reasons).

Beamport preference
The spatial as well as access requirements outlined above underline, that the instrument requires to be positioned at a beam port at the edge of a sector (preferably S12). This might also ease some limitations and the design complexity and associated maintenance issues of the complicated required double pulse shaping chopper system significantly.

1.3.3.7. Add-on user options

The described and specified instrument layout has been optimized for a wide range of applications and (TOF) imaging modalities. While the powerful tool of conventional attenuation contrast neutron imaging requires no more additional instrumentation in the endstation, apart from necessary potentially highly complex sample environment and different detector positions (standard), several other modalities require flexible add-ons in the endstation. An overview of these shall be provided in this section. Some of these, however, are still under development, which will be ongoing besides the instrument construction in order to have up-to-date solutions ready once first neutrons are received. The corresponding organizational structure and whether these add-on developments are part of the instrument construction (or instrument design project) have to still be worked out (but I would consider rather the latter.) Nevertheless, short descriptions are provided as this touches the science case as well as the understanding of the instrument and its modes and requires to be taken into account in many places of the instrument construction, such as non-magnetic environments in the endstation, flexible set-up within the endstation to exchange add-ons, replaceability of components, chopper modes, access along the endstation etc.

It has to be noted that all these user options are foreseen for day-one user operation and their availability is part of the science case of the instrument, as well as they are considered in the budget. Furthermore all these add-on user options will be optimized for installation alignment and de-installation on a measurement to measurement basis. This is partly already state-of-the-art at existing facilities and will allow users to perform different complimentary measurements on the same sample during one and the same measurement campaign without significant sacrifice of beamtime.

a) polarized neutron imaging

For polarized neutron imaging [9-13,28-34], which relates to most science drivers concerning magnetic materials, but also for other add-ons (see below) broadband polarization and analyses is required for the white beam TOF modes. For polarized imaging the TOF approach promises the potential of quantification of even complicated magnetic fields, that is hardly possible at any other source due to flux and efficiency limitations. The basic set-up is not more specific than at existing white beam/monochromatic set-ups at continuous sources [29,30,34]. Different means of polarization and analyses are used in these conveying polarizing supermirrors, solid state benders but also He3 cells. More specific is the task of spin manipulation, i.e. e.g. spin flipping for polarimetric imaging measurements [9-11,33]. Besides adiabatic spin flipping, mupad or TOF-synchronized approaches also considerations for continuous wavelength dependent orientation variations are investigated (Fig. 16)[11]. A complete set-up hence includes: spin polarizer and analyser, guide field set-up and the required field shielding covering the set-up, spin-flippers (adiabatic and non-adiabatic) including such to be ramped with the TOF spectrum of a pulse and crossed for polarimetric approaches. All these components will be installed as potential add-on along the beam path in the endstation covering the last 5-10m from pinhole to the detector. Specific attention has to be paid to have a shortest possible analyser available before the detector for resolution issues. A detailed study for an optimum solution is still to be done, and has to be given time for an up-to-date solution in 2019. The experience of all partners shall be used and the task might become a deliverable of the Dutch in-kind contribution within the next two years. Various other collaborations e.g. with the imaging group at JPARC [28,31], which is very active in this field, are ongoing as well, in order to gain experience with TOF polarized neutron imaging approaches and to provide the best possible solution for ODIN on time.

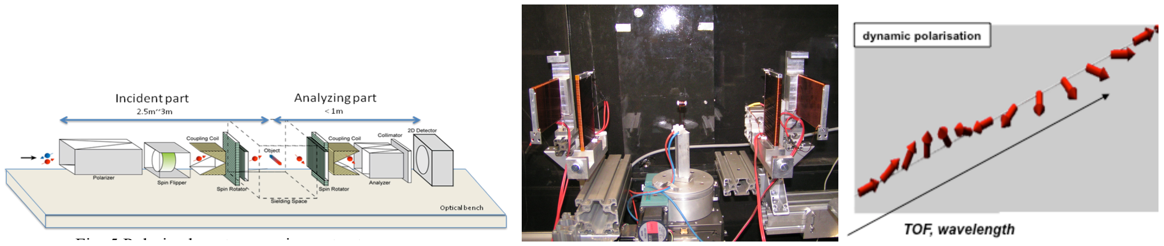


Fig. 16 Polarimetric set-up for imaging at JPARC [28] (top left) and polarimetric set-up used at HZB Berlin [33](mid). Proposed continuous wavelength dependent polarisation orientation for polarimetric imaging and tomography referred to as dynamic [11](right)

b) Grating interferometer (DF imaging)

The grating interferometer (Fig. 17) [35] is the currently most used approach in dark-field contrast neutron imaging in order to use small angle scattering signals combined with real space imaging [18-20]. The TOF approach, however, which aims at quantitative spatially resolved SANS measurements (compare corresponding science drivers) requires the set-up to perform with a broad wavelength range [9,11]. Although a grating set-up is optimized for a single wavelength, recent measurements have proven that a significant wavelength range can be used [20]. Hence, a grating set-up is promising to have TOF potential over a certain range (2-6Å proven) as well. Nevertheless as for longer wavelengths additional grating sets need to be available a corresponding set-up needs to be designed and adapted for different grating sets and corresponding regular and fast changes. Detailed corresponding solutions still require additional work, which is however not critical (in time and it is not critical for basic performance). The maybe most advanced set-up that can be adapted to the requirements has recently been realized at PSI (Fig. 17). On this basis an advanced system will be designed on time for ODIN. However, developments and efforts, also further exploring the wavelength resolved approach for quantification are ongoing in collaboration with PSI, HZB and TUM. It seems to be clear [9,11] that the same approach of quantification used in SEMSANS [21,22] can be applied to the grating method as measurements are equivalent. However, the limitations given by the grating geometry in terms of probable size ranges (app. 200 nm to 5 micrometer, considering sample detector distances 100 mm - 10 mm and wavelengths up to 15Å) has to be investigated in detail, also in order to examine complementarity of the grating method and the spin-echo approach outlined below.

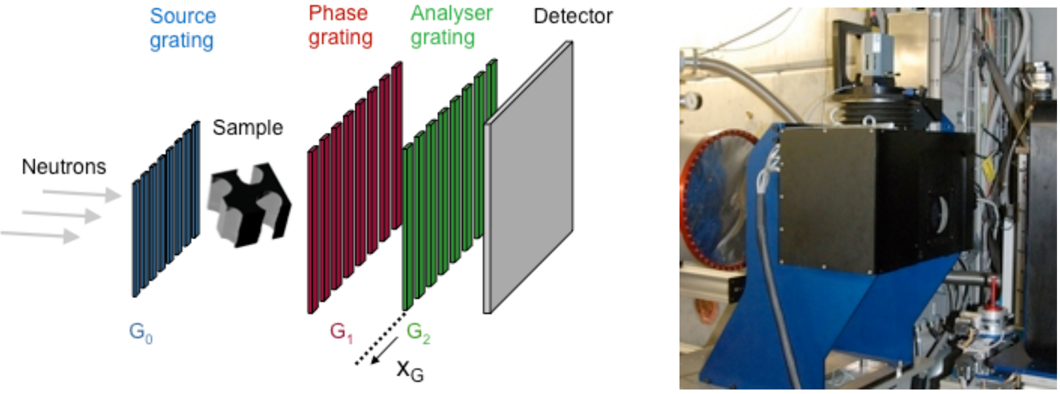


Fig. 17 Principal grating set-up [35]. Note that the first grating is several meters upstream, while the phase and the analyser grating are within a few cm directly in front of the detector (photo: PSI add-on set-up [25]), and the sample can also be placed between them [20]. The gratings are etched structures in Si wavers and the source and analyser gratings are Gd coated absorption gratings.

c) SEMSANS Dutch in-kind

The SEMSANS set-up, which however requires polarization and analyses (see above), is an alternative to the grating set-up for flexible quantitative TOF SANS imaging (compare science case), as has been proven recently [21,22]. This is a completely new technique allowing for the first time for spatial resolved SANS studies, which do not require scanning, and hence to acquire corresponding quantitative structural information simultaneously on a large field of view. A corresponding set-up is the content of the Dutch imaging work unit, which is just about to start. Also here development is hence still ongoing, but the Dutch work unit is well in time for delivering a final concept and design even for first day operation. This however requires shaped fields and potentially wavelength dependent field settings, which are already under investigation and testing in cooperation with the TUD, HZB, KU, UCBerkley.

Developments are promising and risk seems low to fail in this development. The limits this method will face depend on the appropriate detection method, which might involve an analyser grating just like in the grating set-up or a detector with sufficient spatial resolution. Also the limits of magnetic field ranges will significantly influence these. Basing estimates on already realized fields (Fig. 18 [22,36]) in corresponding SESANS and SERGIS TOF experiments first estimates for structure sizes that can be probed from 10 nm up to the micrometer range for sample to detector distances around 100 mm must seem realistic. The feasible beam size for such cases has to however be still explored.

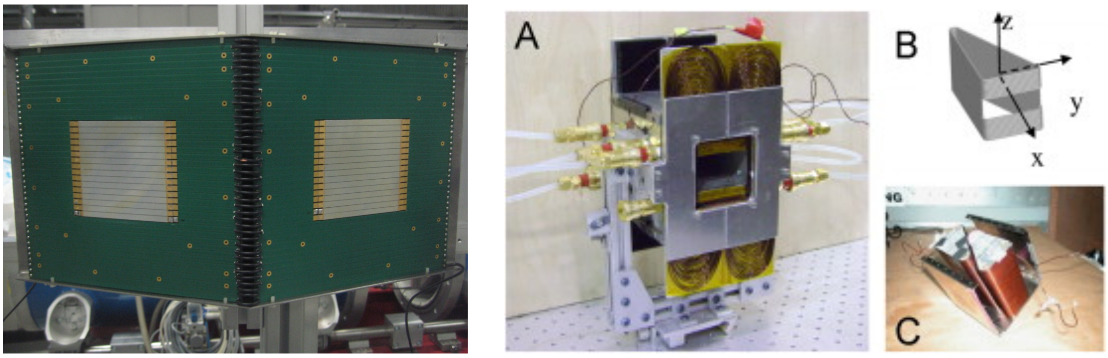


Fig. 18 Different triangular shaped magnetic field regions for TOF applications of SERGIS, SESANS and SEMSANS at TU Delft [22](left) and at Los Alomos [36](mid and right).

d) in-situ x-ray

Another option that is still under consideration is a complimentary x-ray imaging set-up for in-situ x-ray imaging. Here a 90 deg set-up is favored in the moment, also ex-situ set-ups either on the beamline or in a neighboring lab (where it should be usable in any case as well) are considered as they have proven highly productive at other neutron imaging facilities. Technical solutions seem uncritical (PSI [25], HZB [26], TUM [24]).

1.3.3.8. Detectors

Different imaging modes, also conventionally (high resolution, high speed, large/small FOV etc.), depend on different detector set-ups (Tab. 4 top). It is standard at imaging facilities to change detectors depending on actual measurements. Besides these conventional detectors (Table 4, top) ODIN will also require TOF detectors with high spatial resolution. Such are available with high performance for relatively small FOVs already (MCP, Fig. 19) (Tab. 4). However, development is going on to overcome limitations and progress is good and fast [37,38]. ODIN will profit form two other TOF imaging instruments coming online meanwhile (IMAT at ISIS, ERNIS at J-PARC [28], potentially also VENUS at SNS) and corresponding in-house development, all of which seem promising for the future, in particular the schedule for ODIN. However, at least one good solution has already proven to fulfill the requirements with the desired efficiency and both, time and spatial resolution. Tab. 3 provides a basic equipment list of detectors, which would be best suited for ODIN, if operation was started now.

		cost estimate (k€)
detectors (time resolution, MCP and/or new technology)		500
detectors (integrating, 2 CCD cameras, different optics etc)		250
CCD-sCMOS (2 options)		150
conventional 2D detector (low spatial but good time resolution)		300
Total:		1200

Tab. 3 Basic detector equipment for ODIN as for today

Some conventional scattering detectors might also be relevant especially when resolutions in the mm range are sufficient like in some cases of Bragg edge imaging, e.g. for strain mapping, or for spatial resolved SANS measurements in some cases. A fast and easy exchange is standard at imaging facilities and does not pose an issue.

technology	**max FOV**	**min pixel size (µm)**	**time resolution**	**max speed** images/s	**readout**	**DR**	**potential applications**
CCD	40x45	13.5	6s/100ns	1	2s	16bit	white beam/realtime/TOF?
s-CMOS	30x35	25	1s	1	1ms	16bit	white beam/realtime
a-Si	20x25	200	100ms	>10	10ms	12bit	whitebeam/realtime/TOF-DF?

technology	**max FOV**	**min pixel size (µm)**	**time resolution**	**comments development needs**		**pot. applications**
MCP*	2.8x2.8	14	<100ns	FOV limit		all (white beam/realtime/TOF)
EIGER*	1.9x1.9	75	<1ms	FOV limit		all
CIPix	20x20	1000	<µs	resolution limit		all
CMOS-intens.	2.5x2.5	100	200µs	FOV/resolution limit		all
CMOS-integ.	2.5x2.5	200	8µs	FOV/resolution limit		all
µPIC	10x10	200	<1µs	count rate limit		all
GEM	10x10	800	µs?	resolution limit		all

Table 4 Standard detector solutions – key data (top) and advanced imaging detectors for TOF (bottom) *Detectors are named here partly by conversion and partly by detection technology, cause they are referred to like this in the community; for details on e.g. the MCP detector technology see Fig. 19; "?" denote that technology potentially develop towards enabling such applications, but yet questionable;

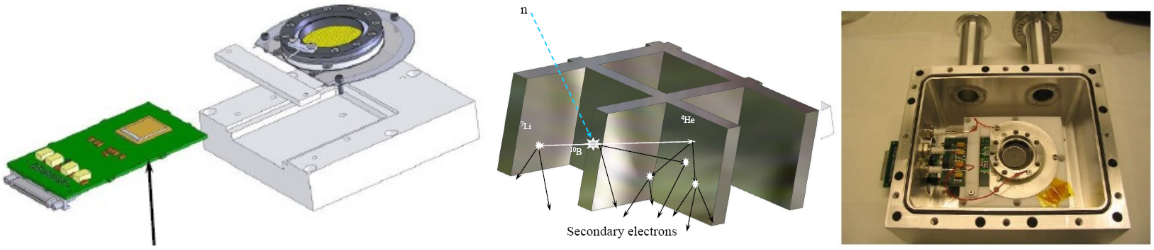


Fig. 19 Images of existing detector solution sufficient for most TOF imaging approaches [37,38]. However, further optimization is ongoing and the active area requires increase in order to allow for bigger, in many cases desired FOV sizes in the 100x100 cm^2 range.

1.3.3.9. Beamstop

The relatively intense and big neutron beam of the imaging instrument requires a sufficient beam-stop, the design of which will still depend strongly on simulations and calculations of background radiation from the guide. Similar solutions like at J-PARC [28], in particular the imaging beamline under construction there (Fig. 20) combining a get-lost-tube and a heavy beamstop will be put in place.

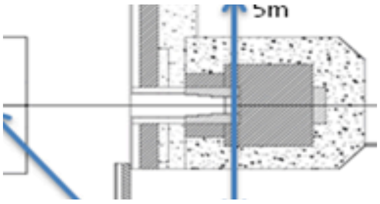


Fig. 20 beamstop layout for ERNIS imaging instrument under construction at JPARC [28]

1.3.4. Operation modes

The instrument layout allows for the following desired operation modes fulfilling all initially defined requirements as well as the needs of the outlined science case.

I. conventional time integrated imaging measurements *(Performance 1 - 10 times best existing and planned)*

Ia) full available spectrum: all choppers off (except T0)

This mode allows for high intensity measurements, e.g. peak spatial and temporal resolution for real time imaging or fast tomography;

Ib) limited spectrum: BWC define bandwidth and spectral location

This mode allows for conventional imaging with high spatial and temporal resolution to choose the optimum contrast through the applied spectrum, (but also to extract monochromatic or multiple monochromatic images for e.g. contrast variation or incoherent background corrections;)

II. low wavelength resolution mode (1% to 10%) *(Performance 4 - 100 times best existing and planned)*

IIa) single frame: BWC define spectrum and measure with wavelength resolution (Fig. 21, left)

This mode allows for conventional imaging with high spatial and temporal resolution to choose the optimum contrast through the applied spectrum, but especially to extract monochromatic or multiple monochromatic images for e.g. contrast variation or incoherent background corrections, allows in particular for quantitative dark-field/2D resolved SANS on limited q-range, qualitative texture and microstructure contrast imaging;

IIb) double(triple) frame: BWC (half speed (one third)) suppress every other (two out of three) pulse(s) and define spectral location (Fig. 21, right)

This mode allows for conventional imaging with high spatial and temporal resolution to choose the optimum contrast through the applied spectrum, but especially to extract monochromatic or multiple monochromatic images for e.g. contrast variation or incoherent background corrections, allows in particular for quantitative dark-field/2D resolved SANS on extended q-range;

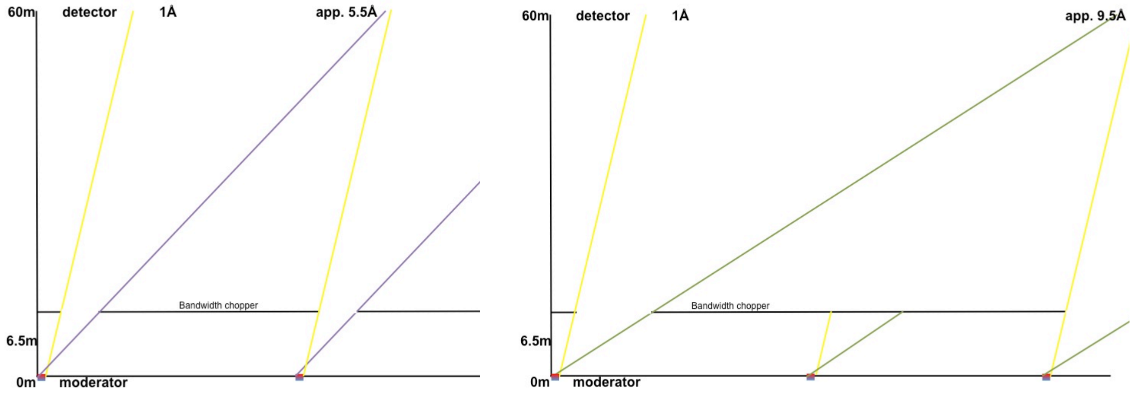


Fig. 21 TOF sketch: Low wavelength resolution mode without (left) and with pulse suppression (right)

III. WFM mode (high wavelength resolution mode; 0.3% to 1%) *(Performance 1-100 times best planned and existing, respectively)*

IIIa) medium resolution every pulse: chopper system fully operational, FOCs at source frequency, PSCs at maximum distance to each other (i.e. 0.5m)

This mode allows for quantitative polarized imaging (with spectral choice) as well as texture and microstructure observation in transmission imaging mode, crystalline phase resolution and phase transition observations; (Fig. 22, sketch 1 and 2)

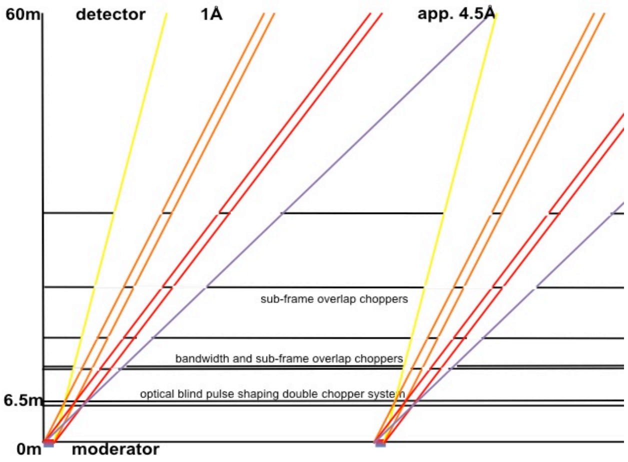
IIIb) medium resolution every second pulse: chopper system fully operational, FOCs half speed, PSCs at maximum distance to each other (i.e. 0.5m)

This mode allows especially for quantitative polarized imaging and expectedly for polarimetric neutron imaging; (Fig. 22, sketch 3)

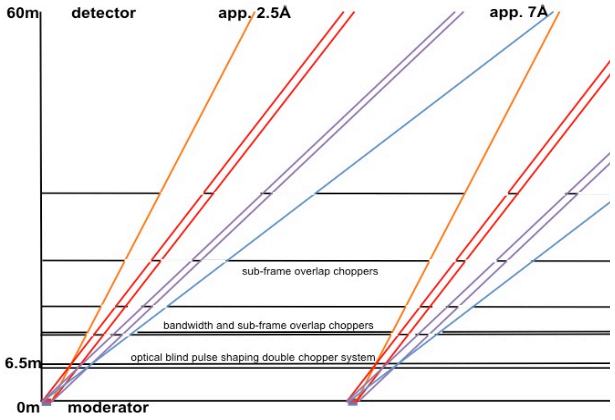
IIIc) high resolution every pulse: chopper system fully operational, PSCs at reduced distance (min. 0.12m), slit between PSCs reduce beam cross section to required size for resolution, FOCs at source frequency

This mode allows especially for strain mapping in TOF transmission imaging mode;

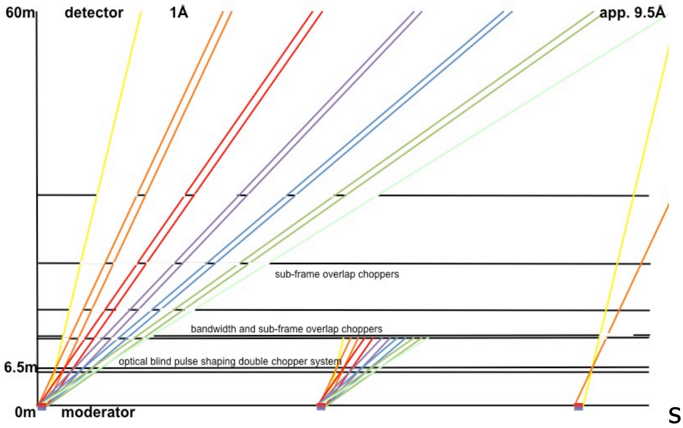
IIId) high resolution every second pulse: chopper system fully operational, PSCs at reduced distance (min. 0.12m), slit between PSCs reduce beam cross section to required size for resolution, FOCs at half speed (Fig 22, sketch 4)



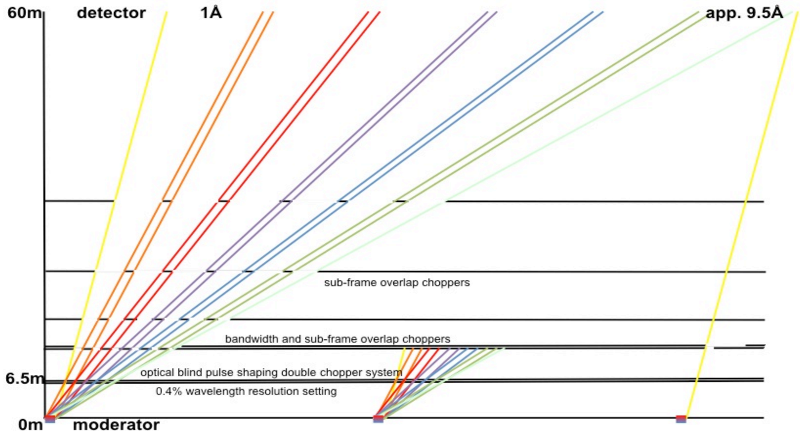
sketch 1



sketch 2



sketch 3



sketch 4

Fig. 22 TOF diagrams for every pulse (two different total frames selected, top sketch 1 and 2) and pulse suppression mode for 1% and 0.4% wavelength resolution (bottom sketch 3 & 4), respectively.

Additional potential modes not yet specified in detail (and hence not part of the science case):
IV. fast neutron/gamma imaging: T0 chopper stopped or de-phased (dependent on direct line–of-sight availability)
V. diffraction mode: diffraction detectors installed, additional pin-hole in front of sample collimates the beam, resolution chosen from mode I-III, (compare potential upgrades below)

1.3.5. Performance

A performance comparison to other existing and planned beamlines is largely based on estimates, especially concerning novel (TOF) modalities, as no reliable numbers from other facilities are available. The values have been extrapolated from provided white beam flux densities at defined but different collimation ratios (L/D).
The performance of ODIN for white beam measurements equals (within some boundaries related to beam homogeneity, which is hard to account for in such simplified comparison) the benchmark performance (i.e. a generic conventional instrument placed at ESS) that corresponds largely to FRM2 and ILL conditions. That means that the added potential of efficient exploitation of TOF imaging modalities does not seem to compromise conventional performance (time averaged). Fig. 23 and Tab. 5 provide an overview of performance for different imaging modalities at world leading existing and planned future instruments.

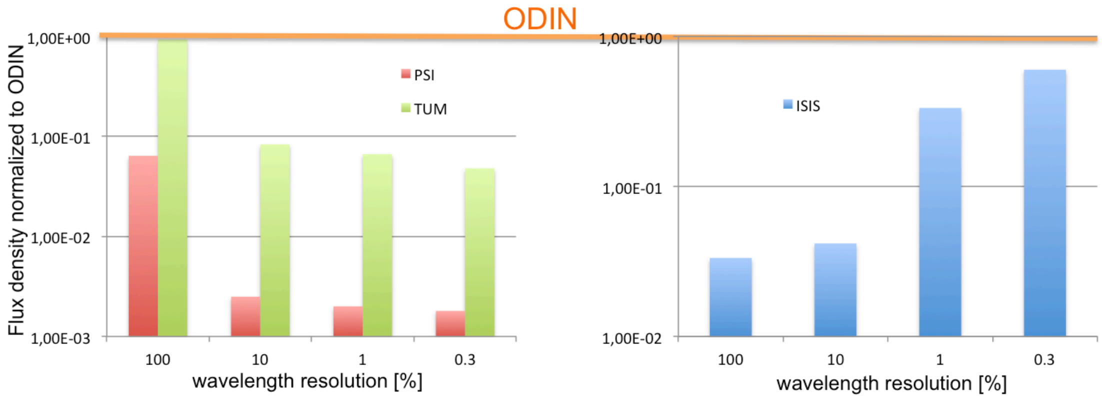


Fig.23 Relative flux density performance compared to world leading and planned instruments

L/D 500	conventional white beam	DF/2D-SANS 10%/BW*	texture/polarized 1%/BW	strain 0.3%/BW
Flux [$s^{-1}cm^{-2}$]				
PSI NEUTRA:	$4.8*10^6$	$1.5*10^5$/4.5Å	$1.5*10^4$/4.5Å	$4.5*10^3$/4.5Å
TUM ANTARES:	$7*10^7$	$5*10^6$/4.5Å	$5*10^5$/4.5Å	$1.2*10^5$/4.5Å
ESS ODIN:	**$7.5*10^7$**	**$6*10^7$/4.5Å**	**$7.5*10^6$/4.5Å**	**$2.5*10^6$/4.5Å**
ISIS IMAT:	$2.5*10^6$	$2.5*10^6$/6.2Å	$2.5*10^6$/6.2Å	$1.5*10^6$/4.5Å

*BW=bandwidth, partly extrapolated (where a broad band seems to be a disadvantage)

Tab. 5 Flux density comparisons of existing and planned imaging facilities extrapolated from white beam flux densities at given collimation ratios and corresponding estimates (size of FOV not accounted for) IMAT at ISIS is marked grey as it does not exist yet but is under construction and hence data is based on simulations only.

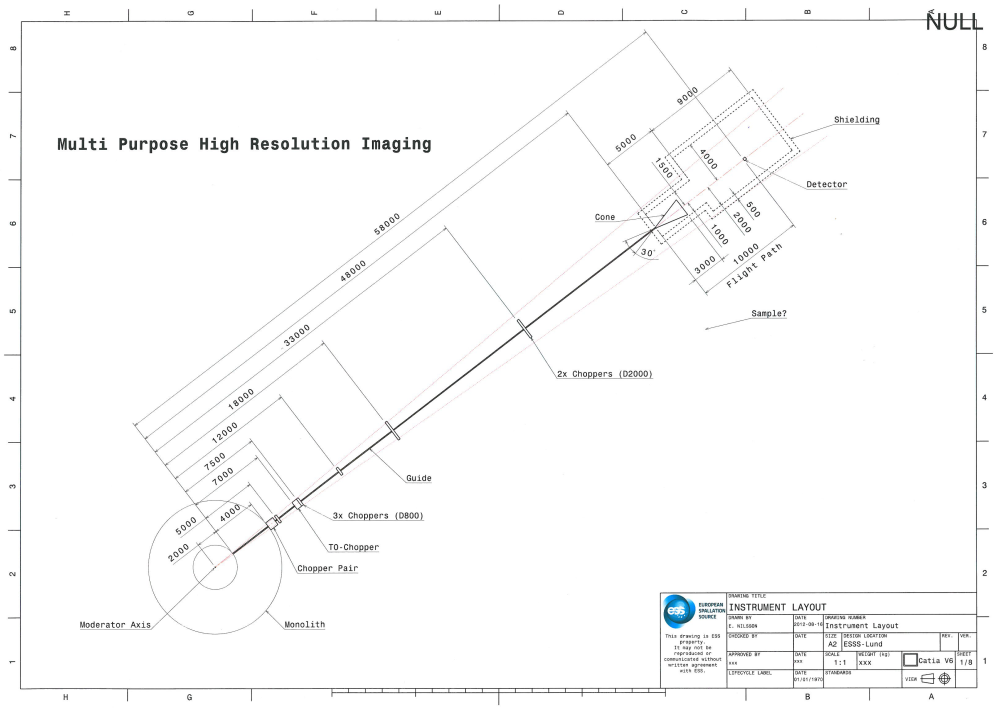
1.3.6. Up-grade options

1.3.6.1. Diffraction detector options

Due to specific applications in e.g. engineering materials and strain investigations complementary detector coverage in scattering geometry is an important option as can also be seen in the concept of the IMAT instrument at ISIS. Hence 90deg detector banks with collimators as well as further detector coverage for complementary scattering experiments, which are straight forward possible with additional collimation through the foreseen slits and wavelength resolution options of the instrument, shall be considered an up-grade option in the moment, based on experiences at e.g. IMAT. This has to be taken into account in the design and layout of the instrument endstation size, shielding and installations. Variable positions of diffraction detector along the beam from the 60 m to pinhole might be considered (e.g. rail system) in order to optimize performance. A day one installation of partial scattering detector coverage will still be considered in detail till the final budgeting and construction start.

1.3.6.2. Fourier/SPEED choppers

Fourier/SPEED choppers mainly applied or investigated for (engineering) diffraction could be an additional option also for Bragg edge investigations in transmission. Such additional chopper implementations carry the potential of significantly higher performance for in particular in-situ diffraction and strain mapping applications of a number of important engineering materials. This is why an according option, and the potential for imaging is still under consideration and shall be proven by corresponding experiments at a Fourier chopper [39] beamline at Dubna. Then these concepts will be re-considered for implementation in ODIN. They might require certain adaptations of the guide system, which have however already been studied, notably also regarding to avoid direct line of sight. Hence, a basis for a decision and slight change in baseline for ODIN will be possible until the first review without impact on the instrument timeline. This is done in-house and based on in-kind results, which are deliverables within 2013.



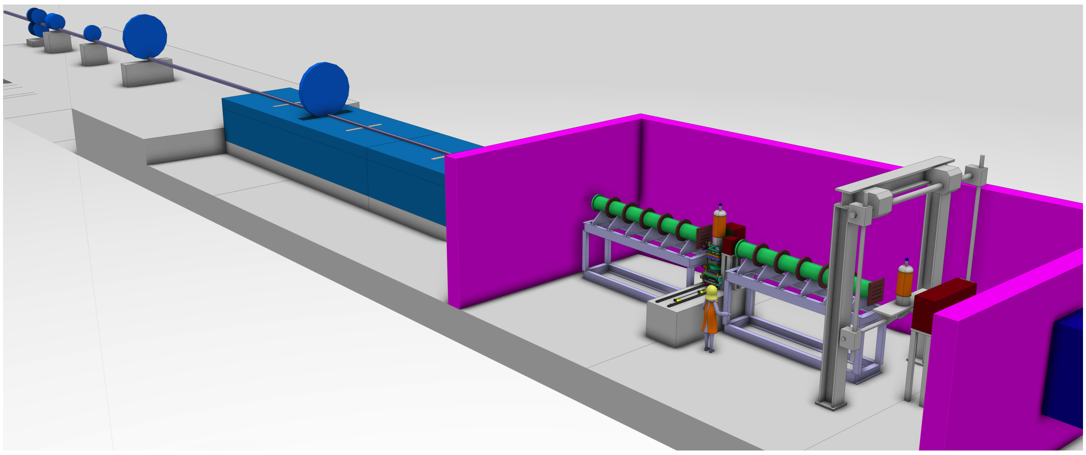


Fig. 24 Preliminary drawing of ODIN within the ESS instrument layout (note chopper positions preliminary and generic) and 3D view.

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1.4 Strategy and Uniqueness

Conventional

ODIN will, when applied in conventional imaging modes, where mainly the time averaged flux counts, be a world leading imaging station, outperforming the most productive imaging instruments in Europe (PSI, HZB) and be comparable, i.e. slightly outperform those at the best continuous sources worldwide (TUM, NIST [40]), all of which are overbooked with industrial and scientific proposals and applications, although the awareness of the capabilities of the technique is still low in industry as well as in many scientific fields, where significant problems can be addressed with neutron imaging. ODIN, with its spectral flexibility can additionally most efficiently be applied, where currently a choice has to be made whether a cold or thermal instrument is to be (built and) applied, while those are both inherent in ODIN.

Novel

However, the basic idea of ODIN is to take full advantage of the nature of the source and the full flexibility it provides in terms of variable wavelength resolution. This enables with ODIN an instrument that provides unique performance for novel methods profiting from low and medium wavelength resolution, which have proven outstanding potential and further development perspectives, such as DF contrast imaging, polarized neutron imaging and Bragg edge imaging. In addition, ODIN will also be world leading for high wavelength resolution Bragg edge imaging, most promising when it comes to strain investigations, even when instruments for the same task become available within the next years at state-of-the-art pulsed spallation sources, which outperform existing instruments with such capability significantly.

Versatility

Consequently ODIN covers the full application range that is on the one hand possible with neutron imaging from todays point of view and that on the other hand profits from and is possible at the ESS. Table 5 in section 1.3.5 provides a corresponding estimate of performance comparison with existing and planned facilities. Fig. 23 displays impressively how ODIN competes with continuous sources for methods not requiring wavelength resolution but outperforms them by orders of magnitude for high wavelength resolutions and vice versa for e.g. an instrument planned at a short pulse spallation source. ODIN, unlike any other instrument will be world leading in all currently known and envisaged thermal and cold neutron imaging methods and will outperform others in most fields significantly. This will enable ODIN to address an unprecedented and unparalleled range of scientific and industrial applications, many of which are not amenable today, as outlined in the science case. In summary that means that ODIN unlike any other instrument currently available or planned will have an outstanding performance in all well known imaging modalities as well as in those expected to provide the most outstanding development and applications in the future.

Future

However, the strategy for the future foresees a more conventional and simple imaging instrument that concentrates on conventional and industrial applications, and which should when available take the load of such applications from ODIN, which then can fully concentrate on the more sophisticated imaging modalities and (scientific) applications, like expected from the exploitation of the novel methods of DF imaging, 2D SANS, polarized neutron imaging and Bragg edge imaging in a TOF mode.

Promise

Another important part of the strategy is, that ODIN is promising to perform from the very first day, even as the full instrument concept is very complex and hence naturally carries some risk, like any instrument project does. However, to realize conventional imaging to start with, requires minor functionality and mainly the guides a slit and a conventional imaging detector in place and the instrument can provide significant results comparable to world leading existing facilities. In case of any problems the capability can be increased step-wise until all modes and capabilities are available with full performance, and even then the further development potential is huge as many promising extensions of methods are still under development and investigation, but can easily be implemented at any time, due to the flexible beamline set-up and modes and the space given and planned for the collimation, sample (environment) and detector positions. These allow for further installations and add-ons at any time. (In this respect it will be important to keep track and be part of the developments especially at the upcoming imaging instrument at JPARC, but also IMAT at ISIS, VENUS at SNS and others.)

Upgradeability (enter complimentary domain)
Concerning potential future diffraction detectors, which would allow to run the instrument as a (engineering) diffractometer for strain and texture measurements - in particular the case of IMAT at ISIS (an imaging instrument, putting a large share of weight towards pure diffraction applications of the mentioned nature) – ODIN can build on experiences made there. Such a shift to an additional focus with a broad scope will also depend on other instrument projects at ESS, like most prominently another imaging beamline focusing on more conservative applications, if built, as well as what materials engineering instruments will be available or foreseen. However, mainly this upgrade is meant to provide additional means of sample characterization in order to complement imaging data for a number of applications.

Build strategy
Parallel development allows for being leading state-of-the-art when getting operational. That involves add-ons, T0 chopper and detector development mainly. We have at least 2 in-kind design & method work units that work far into the next phase, if the instrument is chosen in this round and we plan to carry on such work till at least 1 year before planned operation. As can be seen from the proposal, some final decisions have to be made still on the basis of when final source and construction as well as background and technical feasibility information becomes available. However, these do not pose any obstacles on the timeline and no significant additional risk as most solutions have been worked out with alternatives, which can in case be decided upon and applied at any given and required time.

Synergies
Besides inhouse synergies with other methods in different fields of science and industrial applications, ODIN as a project for future science takes into account the future availability of complementary imaging methods at MAX IV, which will allow for synergies in terms of science as well as user service and corresponding exchange is ongoing. In addition, and also in addition to European partnerships, a close cooperation with surrounding universities active in imaging, possessing e.g. lab x-ray sources, and with a great amount of expertise in image processing, analyses and novel methods has been established. In the moment that has led already to a number of shared PhD positions concentrating on the application of x-ray and neutron imaging but also the exploitation and development of novel approaches and their potential. In the future this might lead to some extend to shared infrastructure like e.g. an image processing lab in the form of a competence centre for scientific imaging as well as shared outreach activities which are already discussed in the moment.

1.5 Technical Maturity

Minimum risk
This instrument project can be considered very low or minimum risk in itself, because just a few basic components in place already allow for worldclass performance providing significant results relevant to all stakeholders. This is the case because already the extraction, guide system as well as any means to suppress the prompt pulse (T0 chopper, potential out of line of sight) and the endstation in place, combined with a conventional imaging set-up and detectors allows for highest performance state-of-the-art operation of the beamline as well

as for low resolution wavelength resolved modalities. The risk for such a basic set-up from the instrument side is considerably low (extraction and guide pose "no risk" according to world leading specialists and supplier) and except the T0 chopper other components are state of the art (mitigation see below). Risks associated to this point are more likely general risks of building up the facility and providing the necessary infrastructure like buildings and supply as well as the source on time. In the very unlikely case other systems and components, in particular e.g. the WFM chopper system causes difficulties or delays, performance to full specifications as given above can be ramped up stepwise. Therefore the overall risk for failure or delay to reach productive operation is at a minimum.
In detail these risks and potential mitigation like already considered alternative solutions in case of technological obstacles are outlined below for the main components.

Extraction

The bi-spectral extraction system, though the first of its kind, does not pose a technological risk as systems of similar complexity and with corresponding mirrors exist. The problem of the harsh environment in which they are placed does not pose a risk anymore, due to latest developments and findings, as is ensured by specialists and providers. Even in the extremely unlikely worst case scenario of a failure of this component world class performance for many techniques and applications in the thermal energy range is guaranteed.

Guide

The guide system is neither a technical challenge in length nor in shape and can be considered state of the art. It therefore does not involve significant risk, if at all, by itself.

T0 chopper

The T0 chopper is certainly a technological challenge as it is the first of it s kind even when comparable to existing or currently developed at, e.g. at JPARC or other pulsed sources with comparable requirements. Currently experiences at such facilities are studied and hopefully soon also the feasibility of the corresponding system for ODIN. However, this component has to be considered a risk and involves certainly certain issues of reliability, maintenance and activation which will be considered carefully in a feasibility study in the engineering phase.

However, mitigation of this major risk has been foreseen and other means to get rid of direct line of sight onto the prompt pulse of the target have been taken into account and can be decided for on time. At least in case the T0 feasibility cannot be confirmed in due time to at least consider it a calculated low risk alternative guide solutions, which lead out of direct line of sight have already been studied and can be implemented whenever a final decision is due. Several corresponding solutions have been considered and only slight performance disadvantage have to be expected, especially concerning beam homogeneity. Corresponding flux losses can be considered to be potentially neutralized by an asymmetric eye of the needle, which would be sufficient for the chopper system but has been avoided so far with respect to beam homogeneity issues, which then might be less relevant with respect to in-homogeneities introduced by an eventual guide bending or kinking. Fig. zz displays only one studied, if not yet fully optimized, solution of a multi channel bender in the constant cross section part of the guide. The presented bender has a corresponding length of 19 m consisting of 10 channels divided by walls of 0.5 mm thickness and currently m=5 coatings on both sides, which however is still subject to optimisations. The radius is about 4000 m. In this case we find a slight reduction of the FOV, however, little impact on the flux homogeneity at the detector. A detailed study of optimizing such component is on the way, including the investigation of the spectral homogeneity for different scenarios. However, roughly it can be estimated that while the guide interruption required for the T0 chopper causes about 10% flux density losses corresponding values for means to move out of direct line of sight range between 20 and 30%. They are hence still acceptable for a mitigation strategy, however, they also imply that potential future demands for methods utilizing fast neutrons or gammas from the prompt pulse are ruled out.

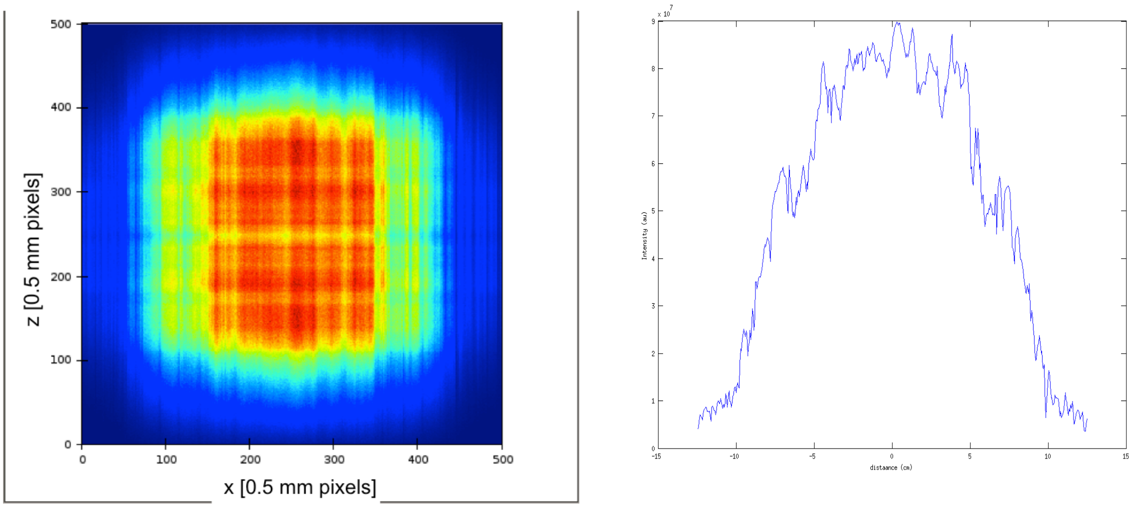


Fig. 25 Beam cross section (25x25 cm displayed) involving a multi channel bender to loose direct line of sight and corresponding beam profile in horizontal direction (±15 cm displayed)

Consequently, the risk involved by the T0 chopper can be mitigated involving relatively minor performance consequences, if necessary. However, a final decision has to be foreseen on time and will be taken care of after intense and careful consideration.

Shutters/beamstop/shielding

Shutters, beamstop and shielding, though essential, can be regarded a minor risk, especially given that corresponding calculations and simulation results from other parties are available on time. In general shutters, beamstop and shielding cannot be considered an obstacle in particular to the beamline itself. Non are technologically a relevant risk factor and can be adapted when required even at later points in time without problem. Required dimensions, positioning and shielding have to be considered timely and with respect to space restrictions by neighboring beamlines, but do not seem critical within currently possible considerations.

WFM chopper system

The WFM chopper system does not pose a significant technical challenge as choppers are slow and mostly well within the state of the art. This is confirmed by world leading experts and suppliers (written statements available on demand). The two movable pulse shaping double disc choppers require a complex support design, where due to the yet unknown geometry of the choppers slight adaptations of the position might become necessary. This however can still be accounted for and as attention is paid to that point the risk involved is considerably low. Should the double disc chopper design unexpectedly pose unsolvable design problems a solution involving two single choppers (Fig. 26) can still be taken into account. However, involved performance losses due to a slit system required in such case between the choppers, has to be considered carefully. For now no reason for such alternative lower performing solution can be identified. The frame overlap choppers with an unconventional large diameter of up to 2m rotate with 14Hz and/or 28Hz (depending on their exact location) relatively slow and consist mainly of windows. Therefore a design even similar to a fan can be imagined and no reason is up to now seen that would imply that their feasibility would pose a risk. Additionally, a similar WFM system is to be tested early 2013 in Berlin and allows for taking into account potentially identified difficulties in time. All these statements rely on the above mentioned expertise of major suppliers.

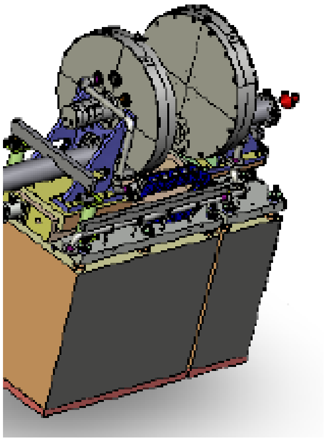


Fig. 26 Potential layout of pulse-shaping chopper system in case only single disc choppers are feasible (example taken from tuneable resolution double chopper system at BioRef (HZB) [17];

Engineering and other components

Although the beamline requires substantial engineering, especially related also to the spatial restrictions imposed by the baseline of 5deg beamline separation at ESS, corresponding maintenance requirements and uncertainties related to the need of some components (e.g. shutters, line of sight etc.) which require significant attention, no concerns concerning the feasibility and the availability of appropriate solutions are obvious, in particular also given the timeline of the project.

Detectors

Detector technology does not pose a major risk to the aims of the instrument as corresponding high spatial and time resolution detectors are available already and improve rapidly, also due to the development of time-of-flight imaging instruments at ISIS, JPARC and SNS. Additionally, new technologies are under investigation and development not only in-house. Given the time-line of ESS and ODIN the right choice of new technology and TOF imaging detectors will be made at the right moment relatively short time before operation as the implementation of detectors which are routinely interchanged at imaging facilities is not critical.

Endstation

The end-station layout takes into account an eventual upgrade with diffraction detector banks. The size, material and thickness of the bunker walls will still depend on radiation and background considerations and calculations, which are still required. It will leave space for the planned add-ons and flexible access along the 10 m flight-path from pinhole to detector like has proven essential at existing instruments. Although the design is far from final it does not involve any technical obstacles and risk is mainly associated not providing the flexibility required. Hence, careful consideration in the design and installations is required at any time.

Add-ons / Methods / Computing

Like specified throughout the proposal, these tasks are not time critical yet and require to be done along the construction of the basic instrument. Availability of optimized set-ups and solutions on time for commissioning period does hence not pose a significant risk. (Besides, part of this might be still a design project in parallel to the construction project of ODIN). However, clear timelines are required and are in place.

CONCLUSION

No significant individual risks to the instrument construction project that lie within the project itself and its technical maturity are to be considered a threat to its timeline and feasibility as mitigation strategies with minor impact on the performance and science case are in place already. All further risks are subject to the ESS project as a whole or range within the average risk of an instrument project of that size, including reliability of vendors etc. Nevertheless, awareness of these risks is big and they are and will be considered carefully in order to mitigate timely within the scope of the ODIN instrument project.

1.6 Costing

The costing for the instrument is summarized in the subsequent Tab. 6. A more detailed version corresponding to the preliminary WBS level 5 for instruments (as has been prepared in cooperation of the Instrument and Program Division in 2012) is available on demand.

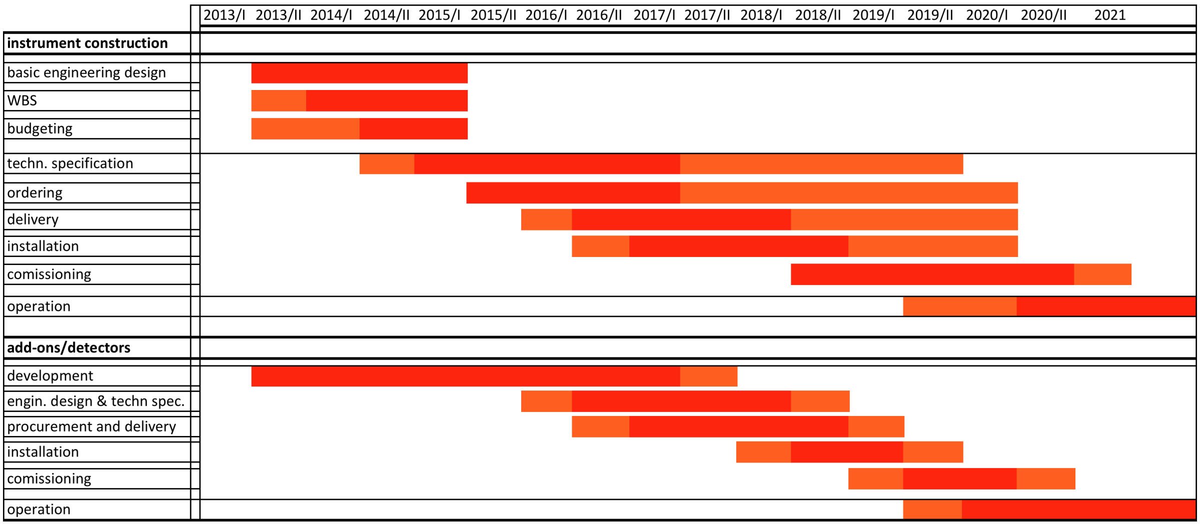
WBS Level 3	**Level 4**		cost estimate kEuro
Instrument ODIN			
	Conventional Infrastructure		160
	Extraction		175
	Guide / Optics		2700
	Choppers		2040
	Shielding		3020
	Sample Area and Sample Environment		500
	Detector(s)		1200
	Special Parts		760
	Electrical Engineering		240
	Computing		50
	SUM		**10945**
	Manpower*		**3000**
	Opt. Diffr.Det.		3000

*based on instrument average estimate made in instrument division

Table 6. Overview cost estimate

Note that for the reason that it must seem fictitious and misleading rather than realistic at the current state of affairs to provide full costing for required manpower in detail, the overall average manpower estimate for building an instrument at ESS derived in the instrument division is used in this costing. Other costs taken into account are investments, i.e. mainly hardware costs, which are based on exchange with companies and other instrument build projects at other facilities as well as available experience.

The subsequent Tab. 7 outlines the timeline for the most important phases of the ODIN instrument construction project, from which in principle a spending profile can be estimated. This however has to be refined and worked out in the required detail in the first phase after the eventual acceptance of the instrument proposal.



Tab. 7 Basic Gantt chart illustrating the rough high-level timeline for the ODIN project (as the project integration of development and construction of add-ons is yet undecided, it has been included separately) (orange marks phasing in and phasing out periods)

2. LIST OF ABBREVIATIONS

Abbreviation	Explanation of abbreviation
HZB	Helmholtz Zentrum Berlin
TUM	Technische Universitaet Muenchen
NIST	National Institute of Standards and Technology
PSI	Paul Scherrer Institut
WFM	Wavelength Frame Multiplication
JPARC	Japan Proton Accelerator Research Complex
ISIS	neutron and muon source at the Rutherford Appleton Laboratory
SEMSANS	Spin Echo Modulated SANS
SESANS	Spin Echo SANS
SERGIS	Spin Echo Resolved Grazing Incidence Scattering
PSC	Pulse Shaping Chopper
FOC	Frame Overlap Chopper
BWC	Band Width Chopper
BW	Band Width
WBS	Work Breakdown Structure
DF	Dark Field
TOF	Time-Of-Flight
MCP	Micro-Channel-Plate (detector)
CCD	Charge Coupled Device (camera)
CMOS	Complementary Metal–Oxide–Semiconductor (camera)
SANS	Small Angle Neutron Scattering
FOV	Field Of View
SNS	Spallation Neutron Source
2D	2-Dimensional
MIN	Minimum
MAX	Maximum
TUD	Technical University Delft
KU	Kopenhagen University
DTU	Danish Technical University
UCBerkley	University California Berkley
FRM2	Forschungs Reaktor Munich 2
ESS	European Spallation Source

PROPOSAL HISTORY

Version	Reason for revision	Date
1.0	New Document	30.10.2012