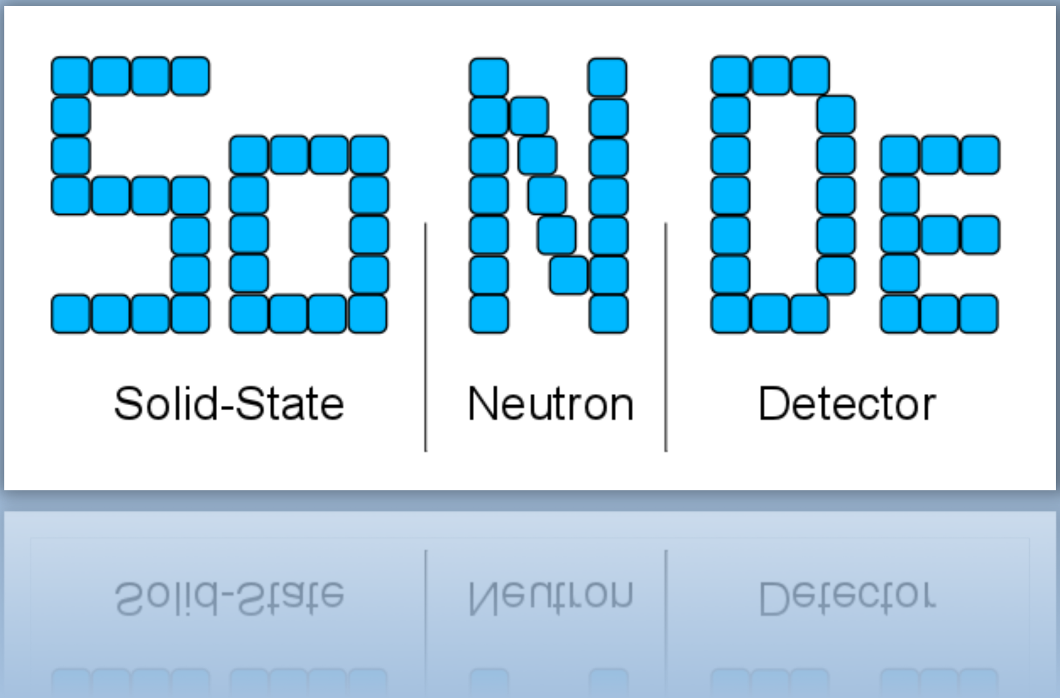
SoNDe

Solid-State Neutron Detector

A Grant Application for the Horizon2020 / Infradev-1 2014 Call by the European Commission



Solid-State Neutron Detector - SoNDe

List of participants

Participant No *	Participant organisation name	Country
1 (Coordinator)	Forschungszentrum Jülich GmbH (FZJ)	Germany
2	European Spallation Source AB (ESS)	Sweden
3	Lunds Universitet (Lund)	Sweden
4	Commissariat à l'énergie atomique et aux énergies alternatives, Laboratoire Léon-Brillouin (CEA/LLB)	France
5	Integrated Detector Electronics AS (IDEAS)	Norway

* Please use the same participant numbering as that used in the administrative proposal forms.

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1. Excellence

The Solid-State Neutron Detector – SoNDe – project aims to develop a high-resolution neutron detector technique that will enable the construction of position-sensitive neutron detectors for high-flux sources, such as the upcoming European Spallation Source (ESS). This includes also the construction of a full-scale prototype as a **research and innovation action**. Moreover, by avoiding the use of ^{3}He in this detector the ^{3}He-shortage, which might otherwise impede the construction of such large-scale facilities, can be alleviated. The main features of the envisioned detector technique are:

- high-flux capability, capable of handling the peak-flux of up-to-date spallation sources (gain factor of 20 over current detectors)
- high-resolution of 3 mm by single-pixel technique, below by interpolation
- high detection efficiency of 80 % or more
- no beam stop necessary, thus enabling investigations with direct beam intensity
- strategic independence of ^{3}He
- time-of-flight (TOF) capability, necessary to exploit maximum flux, with a time resolution in the µs regime
- modularity, improving maintenance characteristics of today's neutron detectors

Compared to nowadays detector technique a gain factor in counting rate of 20 (for ^{3}He detectors) is possible. Such gain factors will be needed to make the best possible use of sources such as the European Spallation Source (Sweden), the Institut Laue-Langevin (France) and the Maier-Leibnitz Zentrum (Germany), which are detailed in the ESFRI roadmap [1,2]. Benefiting instruments at such a facility, among others, would be Small-Angle Neutron Scattering (SANS) instruments such as SKADI [3], which was recently approved by the scientific advisory committee, neutron reflectometers and any instrument needing to detect neutrons with a millimetre accuracy on a large detector area.

Detectors of this kind will be capable of usage in a wide array of neutron instruments at facilities of European interest, which use neutrons to conduct their research, among them the Institute Laue-Langevin (ILL) in France, the Maier-Leibnitz-Zentrum (MLZ, former FRMII) in Germany, Laboratoire Léon-Brillouin (LLB) in France and ISIS in the United Kingdom which are in operation at the moment and the upcoming ESS. At these facilities neutrons are used as a probe in a wide array of fields, ranging from material science to develop new and smart materials, chemical and biological science to develop new drugs for improved treatment of a wide range of medical conditions, magnetic studies for the development of future information storage technology to archaeology, probing historical artefacts on a molecular level without physically destroying them. All these fields nowadays rely heavily on neutrons scattering facilities in their research and thus are in need of a reliable, high-quality neutron detection technique, which will be able to perform well at the new high-flux facilities such as ESS and simultaneously avoid the problem of ^{3}He shortage.

1.1 Objectives

The SoNDe project will develop a working prototype of a new detector technique for the neutron scattering community. This has become necessary, as new challenges have arisen which have to be addressed. These are primarily:

1. Nowadays neutron detector techniques are unable to handle the high-flux of the new upcoming spallation sources. This high-flux capability also needs to include high count-rate capability, to be able to operate in time-of-flight (TOF) mode.

2. High-resolution detectors are typically using interpolation techniques between neighbouring channels. This implies a large effort in readout electronics and limits the achievable count rates. Thus, experiments, which need large-area detectors with simultaneously high-resolution and high count-rate capability are very cost intensive and are hard to realize.
3. ^{3}He is becoming more and more rare and is instrumental for one of today's most prominent neutron detection techniques, thus acquiring a strategic independence of it seems necessary in the near and intermediate future.
4. As neutron facilities are used in the research of ever-larger scientific communities easy maintenance and usage are becoming more and more important to cater all the needs addressed to a modern neutron scattering facility.
5. As more and more complicated instrument designs are developed, an adaptable geometry becomes necessary, to address each user's specific needs.

From improvements in these areas a wide range of users will be able to benefit, as they address the issues faced by the scientific neutron scattering community as a whole. We want to address all these issues simultaneously by developing a working prototype of a scintillation based neutron detector technique, which then can be adapted to a wide range of different applications in neutron scattering facilities. The above issues will be addressed as follows:

1. The maximum count rate of scintillation based detectors are primarily limited by the dead-time of the conversion material, most commonly ^{6}Li, and the electronic detection limit of the photomultipliers detecting the light flashes from scintillation events. Thus, today's neutron detectors are limited by the detector electronics and the dead-time of the photomultipliers, while the dead-time of the conversion material is not an issue. We therefore propose to use multi-anode photomultipliers (MaPMT), which are by a factor of 100 smaller than the ones used today, thus effectively increasing the possible detectable neutron flux per sample area by the same factor. As their calculated counting rate is at about 50 kHz (per 5x5 cm^2 MaPMT module) [4] we predict a theoretical counting capability of around 20 MHz for a 1x1 m^2 detector, which at this time is presumably only limited by the available detector electronics. The gain of at least factor 20 compared to state-of-the-art detectors is thus based on segmentation of the detector. This in turn also allows trading-off necessary flux capability for resolution and vice versa in each single experiment, depending on the needs of the specific setup, by combining larger segments of photomultipliers together.
2. Today's large-area detectors have a minimal resolution of 8x8 mm^2 (^{3}He detectors) down to 5x5 mm^2 (scintillation detector with Anger-Camera interpolation), depending on the used technique. However, in the case of the Anger-Camera, where the physical resolution in the cm range is increased down to the mm range, an array of 3 by 3 photomultipliers is used for the detection of each single neutron, thus effectively cutting down the maximum counting frequency by a factor of 10. The resolution of 3x3 mm^2 on large area detectors will be achieved by single-pixel photon detectors, which are independent of each other. As an additional advantage a single damaged photomultiplier does not render a huge area of the detector blind. It is also conceivable to couple these small pixel photomultipliers together according to the Anger-principle, thus increasing the possible resolution of the detector even more at the cost of a lower counting frequency. This technique furthermore allows for an adaptable resolution, as MaPMTs with different resolutions are available. The highest physical resolution of 3x3 mm^2 can be used together with the Anger-principle, where the resolution is improved down to 1.5x1.5 mm^2 by evaluating the crosstalk between different pixels.
3. ^{3}He is not needed for this detector technique, thus rendering it insensitive to resource shortness on this part. Several conversion materials will be tested, to find the best possible combination of the proposed MaPMTs and the conversion material. By being independent

of ^{3}He we also project a significant reduction in cost, compared to ^{3}He detectors, while maintaining all the other benefits.

4. By design the MaPMTs are on replaceable 5x5 cm^2 modules, which will be coupled with their own counting electronics. Thus it is extremely easy and fast to replace a damaged module and operation of the neutron scattering instrument does not have to be interrupted for extended periods of time for repair or maintenance, which can take up to some months with state-of-the-art detectors.
5. By combining any number of the 5x5 cm^2 segments nearly any conceivable geometry is available, even if the single segments are not mounted in plane but for example on a spherical surface or a fraction thereof.
6. Due to the high flux capability the state-of-the-art use of beamstops in areas of extremely high flux may become unnecessary. This not only allows for scientific measurements in a manner not possible with today's technology, but also removes an additional component from the detector and thus reduces the probability of technical failure. Especially for SANS instruments it is moreover very important to accurately measure the transmission. For TOF instruments this means to exactly measure the transmission as a function of wavelength to be able to calculate absolute intensities, which is an inherent advantage of SANS experiments over comparable methods. Thus, the quality of the results of such measurements will be greatly improved without a beamstop and push the state-of-the-art for this highly oversubscribed investigative technique.
7. The integrated electronics-based pulse processing we envision for the SoNDe detector concept will be an elementary part of the discussed design. It will allow for the needed segmentation, which is not achievable with today's technology.

In order to approach all these challenges we have identified a set of objectives that have to be reached:

1. Identify a suitable material for neutron conversion, which combines a low dead time with a low probability of phosphorescence in the case of high exposure to neutron radiation. Also a low scattering background is desirable.
2. Conduct market research to identify all possible suppliers of suitable photomultipliers. As of this date, Hamamatsu is able to supply photomultipliers with the desired specifications, but other companies may also be able to do so. The market research will thus concentrate on whether there is a European supplier of a comparable technology, or if a technology available from a European supplier can be adapted to the specific needs of the project.
3. The identification of alternate potential users, apart from large-scale neutron research facilities, will also allow other fields to benefit from the innovations in this project. One possible candidate for example is the medical application of positron-emission tomography.
4. Market research and financial planning for potential users. This way we want to find potential users, draft a financial concept for distributing products that may come out of the project (services, hardware, IP) and compare to current technology also in terms of financial feasibility.
5. Construct radiation hard counting electronics for data collection or identify a possibility to remove the electronics to an area with lower intensity or construct appropriate shielding. The MaPMTs will also be evaluated for radiation hardness and appropriate shielding will be developed if needed.
6. Combine several MaPMTs and the conversion plate to a technology demonstrator. This first model will help identifying issues that will arise when building a large area detector.
7. Assess if the primary beam area can withstand the neutron flux on a spallation source. If additional attenuation is needed in the high intensity regions of the detector, identify a suitable attenuation technique.

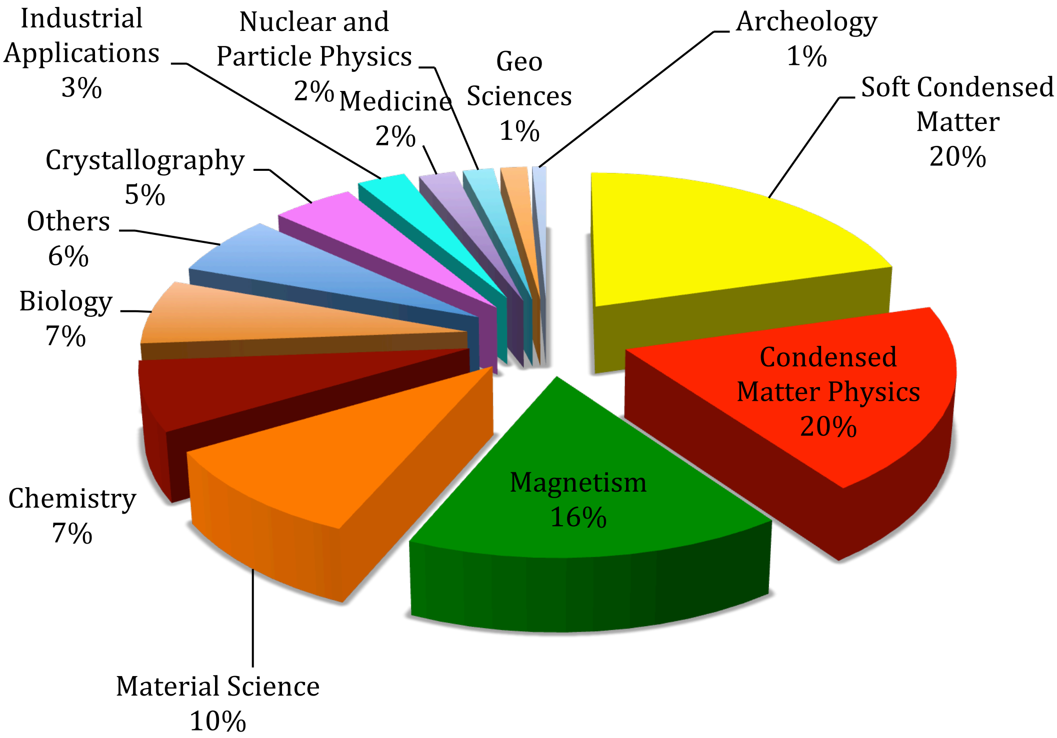

Fig. 1 Scientific fields of experiments conducted at FZJ operated neutron scattering facilities between 2011 and 2013. While condensed matter, soft condensed matter and magnetism take up the major part, there is a wide range of other scientific fields working at neutron scattering facilities.

When all previous objectives have been reached, we will construct and build a prototype of a large area neutron detector, feasible for operation on high-flux neutron sources, such as spallation sources. This large-scale prototype will then be installed in a SANS instrument in a European research facility to demonstrate its capabilities to the user community. A possible candidate for this is the SKADI SANS instrument [3] at the upcoming ESS in the ESFRI roadmap.

1.2 Relation to the work programme

Specific Challenge

In order to equip modern research infrastructures working with neutrons with suitable detectors it is of paramount importance to design new neutron detectors, which meet the requirements of neutron scattering research today and in the foreseeable future. They are the basis for new cutting-edge neutron research facilities, which in turn allow for continuously high-performing outstanding research. As it is also planned to provide a working prototype the European manufacturing industry will gain experience in delivering and assembling all components needed for this crucial infrastructure. This **technical design** study and **research and innovation action** will deliver the knowledge and expertise needed to built a neutron detector that is an important part of the infrastructure of large-scale neutron research facilities. These in themselves are virtually always of European dimension and interest, as their construction usually requires the joined effort of several partner countries. Additionally to being the basis for instruments at new facilities, which are being planned now or in the foreseeable future, this neutron detector can also be considered when upgrading existing research facilities and thus enhance their performance.

In terms of scientific application one can hardly overstate the range of addressed issues. In virtually any field from material science, medical and biological sciences even in archaeology neutron scattering methods are used today (see Fig. 1) [5]. Neutrons offer the possibility to investigate properties of materials that are hidden to most other probes, here most significantly magnetic structure, or allow detailed structural analyses by adapting the contrast of a scattering experiment by choosing appropriate isotopes of the same element, thus keeping the chemical properties constant while varying the contrast of the measurement (referred to as *contrast matching*). Up to now these measurements helped improve and develop materials for air and space engineering [6], new delivery methods for drugs [7] or the investigation of complicated magnetic structures [8-12], which are a strong candidate for developing future data storage technology. The capability for these developments is paramount to future scientific and industry research.

Another issue, which is in itself of an European dimension and interest is the present day dependence of ^{3}He for building high-flux capable neutron detectors, as are implemented in virtually all neutron research facilities nowadays. By construction of a technical demonstration model as well as a working prototype of a large area neutron detector with a high resolution, this dependency on ^{3}He can be alleviated or even removed for the future construction or upgrade of existing large-scale neutron research facilities. The strategic independence of ^{3}He will thus allow for future high-profile research in Europe, independent of outside suppliers.

Scope

The SoNDe programme will develop and build a final prototype of a high-flux capable, large-area neutron detector with high resolution, which is an instrumental key technology in the construction of future large-scale neutron scattering facilities, which is classified as a **research and innovation action** by the work programme. A new neutron detector concept will help the complete neutron scattering community in their respective fields of science, ranging from biological and chemical studies, which can help improve future drugs and their application, to studies of magnetic materials for future data storage technologies. By making the new facilities, such as ESS, less dependent on ^{3}He SoNDe will also make sure these large scale neutron scattering facilities are not impeded in their usability by a shortage of ^{3}He and thus can be used to their full capacity. Moreover, ease of maintenance and repair will cut down repair and maintenance times and costs, thus making more time available for scientific measurements. As the ESS is prioritised in the ESFRI roadmap [1,2], a development supporting outstanding operation will also benefit future Infradev calls and strengthen the ESFRI strategy.

In terms of legal feasibility we will explore several options for a high degree of freedom in terms of proliferation of the detector concept and technique to the community. This will include, but not limit to, the exploration for access to the intellectual property and supply of technical components to companies. As for the financial feasibility of this new class of detectors we anticipate costs equal to the current techniques. This will even improve in the future, as ^{3}He is a limited commodity, which will become more expensive in the future, thus increasing the costs for ^{3}He based detector solutions. However, detailed analyses of the cost structure for future users will be part of the market analyses during the dissemination. All issues connected with legal and financial feasibility and comparisons to competing technologies will be discussed in the deliverable report “Financial and Legal Feasibility report” (deliverable 5.7).

Concluding, the performed activity within the scope of the project will be the drafting of concepts and engineering plans for the construction, as well as the creation of final prototypes for key enabling technologies and implementation plans for transfer of knowledge from existing prototypes to the new research infrastructure, as stated in the work programme of Horizon2020.

1.3 Concept and approach

Overall Concept

The most prominent arguments for the development of a new type of neutron detectors are the limited tolerance to the peak-flux of new spallation sources of today's detector techniques and the alleviation of the effects of the ^{3}He shortage. While the first limitation would prevent a usage of the new high-flux neutron sources to their full capacity, the ^{3}He shortage will not any more allow the building of a number of ^{3}He based detectors simultaneously as needed for large scale structures such as the ESS.

Furthermore, in order to reach a high spatial resolution the current detector techniques rely either on a combination of a small detector for high spatial resolution and a large area detector with a lower spatial resolution or only a small area detector is used. The proposed modular concept utilizes MaPMTs and integrated electronics. This allows the design of large-area high-resolution detectors.

In order to operate large-scale neutron research facilities in the future it is instrumental to explore alternatives to nowadays' major neutron detection technique for high flux sources, which is ^{3}He based. As ^{3}He is a limited commodity, whose supply is highly unlikely to increase in the future and whose supply is already strained today, achieving independence of ^{3}He will remove a major obstacle for high-quality detectors on future high-flux neutron sources.

One additional issue to be addressed is the ease of maintenance and repairs in large-scale facilities, where a major breakdown of any crucial component, such as the detector, will cause a downtime that impacts a wide group of researchers. This is due to the fact that the researchers are usually scheduled for approximately 2-3 days of time for their experiments and at the high overbooking factors reached in neutron research facilities make it often impossible to reschedule skipped experiments. Thus a fast and reliable mode for repairs has to be kept in mind, which is accounted for by the modularity of the proposed detector. By this modularity relatively low cost spare parts can be kept in stock to perform repairs in a matter of days instead of months as with the current technique.

Most of these issues are resolved by the basic design concept envisioned for the SoNDe detector. After describing the basic concept we will give additional details to each issue in the rest of this section.

SoNDe is a concept for a scintillation-based detector with multi-anode photomultipliers. A schematic drawing can be seen in Fig. 3. The detector consists of an array of segments of MaPMT (see Fig. 2) with a corresponding counting electronics chip. There are already solutions on the market for the single components, which will have to be assessed in terms of feasibility. Counting and conversion are independent for each of the segments. In Fig. 3 b) the side view of the detector shows the ^{6}Li scintillation-glass and the MaPMTs with counting electronics. In this view the neutrons are coming from the left hand side and are converted to photons by a scintillation process. These photons are later counted by the MaPMTs. Apart from ^{6}Li there are also other conversion materials available, which will be evaluated for feasibility in this design study. Finally in Fig. 3 c) there is 3x3 MaPMT array. Each of these is independent of the others in terms of counting. With theoretical counting rates in the range of kHz for a single photomultiplier, each MaPMT of 5x5 cm^{2} will allow counting rates around 50 kHz, resulting in approximately 20 MHz for a 1x1 m^{2} detector. (as compared to 300 kHz for scintillation detectors and 1.5 MHz for ^{3}He detectors today). Today's detectors just about reach into the low MHz range for the complete large-area detector with approximately 1x1 m^2. This amounts to a gain factor of approximately 20 over current ^{3}He detectors and will thus allow the best use of high flux neutron sources, such as the future ESS.

The spatial resolution of current neutron detector technology is in the order of 8x8 mm^2 for most large-area capable technologies (^{3}He, scintillation with Anger principle) in the case of large area detectors. Small area detectors (Si-based CCD, Gas Electron Multiplier (GEM)[13]) on the other hand can go to extremely high spatial resolutions down to 50x50 µm^2, however they either are not technically feasible for detectors larger than approximately 15x15 cm^2, they are too expensive per area or both. SoNDe will resolve these issues by combining a high spatial resolution that is appropriate for a wide array of neutron scattering instruments (such as small-angle scattering, reflectometry and grazing incidence small-angle scattering) with costs in the order of today's large area detectors (about 1.5 M€ for a 1x1 m^2 ^{3}He detector [14]). The high-resolution MaPMTs together with an appropriate conversion material will thus combine to cater for the needs of a large community of neutron scientists.

Already today there are some detectors that are independent of ^{3}He and some are capable of being used in a high-flux source, but not simultaneously so. While getting more and more rare, ^{3}He is still the gold standard for high-flux neutron detectors. By the high counting frequency enabled by using MaPMTs behind a conversion material this obstacle will be overcome by SoNDe, while maintaining high spatial resolution. Moreover, already today ^{3}He shortage is an issue in planning large-scale neutron research facilities on a global scale [15]. Independence on ^{3}He will thus make it possible to built facilities of European interest and international recognition without being impeded by the shortage (see Fig. 4) [15]. The severity of this lack is also corroborated by the fact that the supply in the USA as a major supplier will be fully depleted by 2024 and that there are only 4000 litres/year available for auction to cover any non-US government use. The US department of energy is already looking heavily into alternatives, without having found any up to this date [16].

Most current neutron detector concepts are monolithic in nature or so highly integrated that repair and maintenance of any single part is virtually impossible (see section 1.4.1, *State of the Art*), thus making it necessary to remove and repair the complete detector, which results in long down times of the affected instrument. By making the electronics of each MaPMT independent of the others and supplying each module with its individual conversion area it becomes possible to repair detectors like SoNDe with relative ease and short downtimes. Single MaPMTs along with conversion material and electronics can even be kept in stock and be replaced in a matter of some days instead of weeks or months, as is the case for the other detector techniques. Being able to keep relatively inexpensive spare parts in stock is a major advantage, especially in high-profile large-scale research facilities, where especially manufactured parts are needed that often have a long delivery delay.

All these conceptual advantages of SoNDe over existing neutron detector concepts attest to the need to develop SoNDe as a new detector technology in order to be able to use future large-scale neutron research facilities of European interest to capacity. This way the European scientific community will be able to perform outstanding research on future neutron sources and it is even possible to upgrade existing neutron sources to improve on their performance.

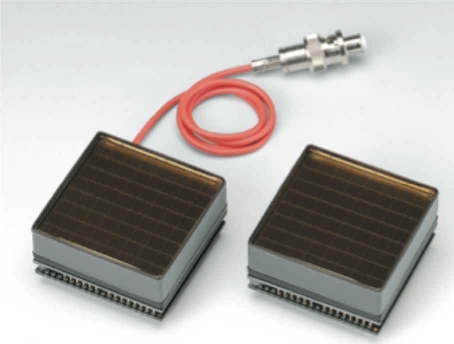

Fig. 2. H8500 MaPMT with high-voltage connector. The size of the effective area is 46.25x49 mm with 1.5 mm of dead space around the detection area.

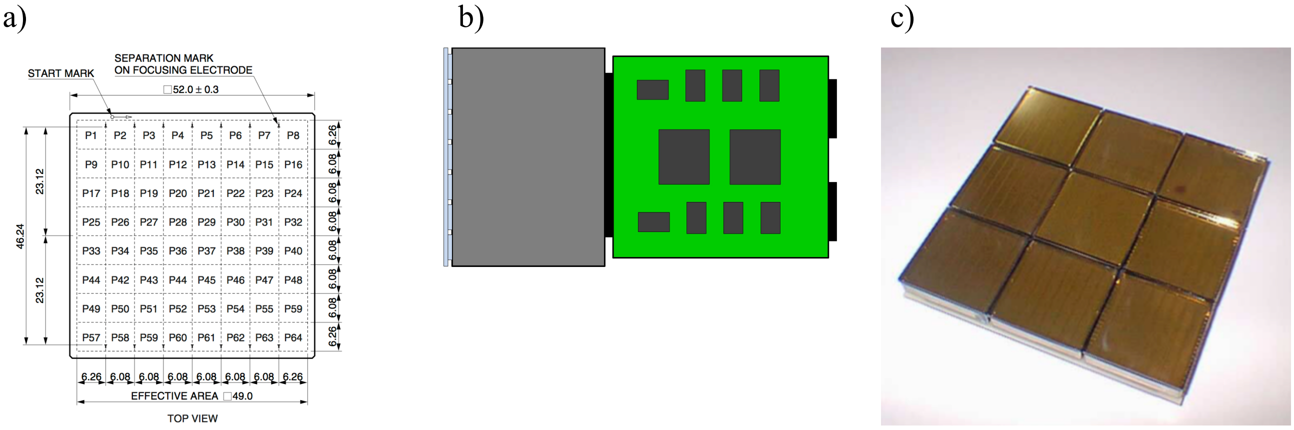

Fig. 3 Schematic of the SoNDe detector. a) technical sketch of H8500 MaPMT front. [4], b) side view of a single photomultiplier with Li-scintillation converter glass, multiplier-array and counting electronics (from left to right) and c) array of MaPMTs as envisioned for the SoNDe detector concept [17].

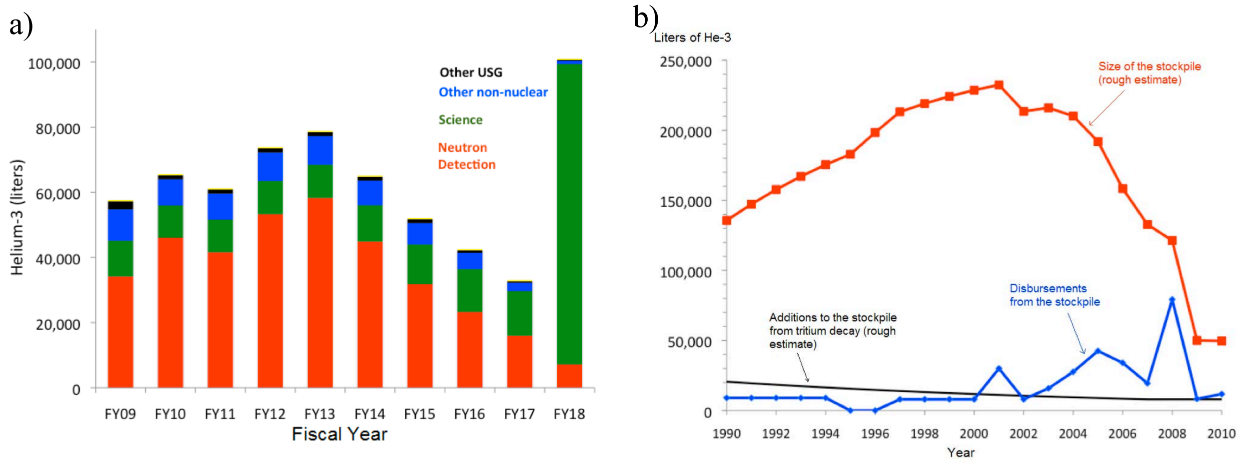

Fig. 2. a) Projected demand for ^{3}He. (USG: US Government). The neutron detection in red is not for scientific purposes but mainly for detectors for border control. The increase in 2018 is due to an allotment of ^{3}He to the Spallation Neutron Source. b) development of ^{3}He availability [15].

Positioning of the Project

Relevant techniques for the single components of the SoNDe detector technique are available. However they have yet to be proven to be feasible for the actual construction of a large-area neutron detector. For most of the techniques alternatives are available and have to be tested for finding the optimal combination. The single technology components have been identified as:

1. Conversion technique: Here there is a wide area of possible materials that can be used, most important ^{6}Li and ^{10}B. Both of these materials will be tested for high conversion rate, low background, low phosphorescence and radiation hardness. (TRL 8 – system completed and qualified: A range of different conversion techniques is already available in the detectors of different neutron scattering experiments. However these need to be assessed for applicability for this specific concept.)
2. Photomultipliers: Although there are already MaPMTs available on the market these have to be tested in terms of their radiation hardness as well as for low background. Alternative suppliers may be able to deliver solid-state photomultipliers that are better suited in both these areas for the application in a large area neutron detector. (TRL 5 - technology validated in relevant environment: The system is already on the market. However it has to be tested to meet the specific requirements of this project.)
3. Attenuation technique for measurement of the direct beam: At this point it seems possible that scintillators combined with the MaPMTs are capable of detecting the full intensity of a direct beam, even at a pulsed, high-flux neutron source. Should this assessment be inaccurate an appropriate attenuation technology (Lithium or Boron attenuators) will have to be tested. This way the usage of beamstops to block the direct beam as in today's neutron detectors becomes obsolete. (TRL 7 - system prototype demonstration in operational environment: Neutron attenuation is state of the art in today's neutron scattering instruments. However the applicability of a custom-shaped attenuator to avoid the need for a beamstop has not been attempted yet.)
4. High frequency integrated counting electronics has to be adapted for neutron detection. (TRL 5 - technology validated in relevant environment: The high frequency counting electronics is available and works in other environments. There is also already counting electronics in today's neutron instruments. However this new counting boards need to be adapted for the use in a high radiation environment.)

Technology readiness assessments as in annex G of the work programme are indicated in brackets. Concluding the issue of technology readiness, SoNDe as a complete detector technique comprises no technique that is as of yet unproven in a laboratory environment. Most single components have already been used in other environments and are already available on the market, but their combination is as of yet a challenge. The main part that will be developed completely new is the counting electronics, which however poses little technological risk.

Linked Research Activities

The neutron research community is a strongly interconnected and international community, where most of the development is only possible in a coordinated effort, either by several institutes in one country or even internationally. To illustrate the interconnectedness of the field we give a selection of examples that feed into and benefit of this proposal mutually.

As already mentioned, the ESS, prioritised in the ESFRI framework [1,2], will need a reliable high-flux capable neutron detection technique, applicable in, among others, SANS and neutron reflectometry setups. Also, advancements in systems integration into large-scale facilities as well as data evaluation concepts developed at the ESS will feed into the SoNDe detector project.

The FZJ has already built and operated the KWS 1/2/3 SANS instruments at MLZ, Garching, Germany, for several years. The experience and expertise from this will feed directly into the planning and construction of the SoNDe detector concept, as the requirements towards such a detector are known to the staff, that will for a large part also be part of the SoNDe project.

Especially at the KWS 3 SANS instrument a small multi-anode photomultiplier has already been installed and operated. However its technical and cost restrictions prevent the construction of a large-scale detector using the same technique. Nevertheless, concerning the conversion technique and data readout the operation of this detector will give valuable a priori insight that will help constructing a detector following the SoNDe concept.

The same level of expertise in operation of such large-scale instruments is also maintained at the LLB with the operation of the TPA spectrometer (represented by S. Désert). There the possibility to test such a detector with high-resolution image to determine physical resolution is unique. Additionally, facilitated access to a high-flux irradiation station will be needed in order to test the high-flux capability of the detector, needed at the ESS. Such tests at other facilities are only possible with a considerable amount of preparation.

Instruments both at the MLZ and the LLB are used by an international user community, which also allows for the intimate knowledge of the needs of the users of such facilities.

The ESS in turn, as the upcoming largest European neutron scattering infrastructure, is currently developing an array of possible techniques and needs to do so to implement its instrument suite in the best way possible as to meet the ESFRI prioritisation. Thus a work group dedicated to the integration of detectors into large-scale facilities has been founded and will be instrumental in the completion of the SoNDe project. A close collaboration between Lund University and the ESS is aimed to maintain a high scientific standard as well as close connection to the scientific community.

IDEAS as a company strongly involved in high-technology research by its very profile adds substantially to the expertise needed to successfully complete this project (for details see section 4 and 5 of this application).

All these activities in concert allow for the expertise and know-how required to build a neutron detector based on a new concept such as SoNDe.

Approach and Methodology

After identifying the appropriate materials and suppliers a demonstration model will be constructed. With the experiences gained by this demonstration model, a full-scale detector can be built. The respective deliverables will be (milestones are printed bold):

- **Building a 1x1 segment hardware demonstrator to show the feasibility of the concept**
- Writing an internal report for the research on the material feasibility of the aforementioned demonstrator and publish the results in a peer-reviewed journal
- Assessing the radiation hardness of the counting electronics and prepare an internal report
- **Building a 2x2 segment hardware demonstrator to test for the scalability of the technology**
- Testing and evaluating the 2x2 demonstrator and publish the results in a peer-reviewed journal
- Preparing an internal report on the electronics of the 2x2 demonstrator
- Preparing an internal report on the mechanical issues of the 2x2 demonstrator
- **Preparing an internal report about issues regarding large-scale system integration and scalability of the 2x2 demonstrator**
- **Constructing a large-scale prototype (1x1 m^2)**
- Publishing a paper about the large-scale prototype in a peer-reviewed journal

- Perform semi-annual meetings to assess the progress at the different project stages. These meetings will also give the possibility to adjust the work plan to unforeseen issues and as a possibility to assess potential IP management issues (harvesting meetings).
- Continuously publish findings on conferences.
- Finding additional applications for the proposed concept or the developed innovations or parts thereof
- Performing an audit half a year before the end of the project, to assess the success of the project
- Holding a workshop for potential users to identify applications for the innovations and find potential sites for detectors employing the SoNDe concept
- Creating a website that reports on the project's results and progress
- Perform market research and financial planning for potential users. This way we want to find potential users, draft a financial concept for purchasing products that may come out of the project (services, hardware, IP) and compare to current technology also in terms of financial feasibility.
- Create financial and progress reports to European Commission.

First initial tests of possible alternatives for single components (conversion material, different MaPMTs) will enable us to draft an overall concept in detail for SoNDe and lead to the creation of engineering plans.

In order to prove the concept feasible and superior to current concepts in those aspects laid out in the *Overall Concept* section, a final prototype will be needed. A potential location for this prototype is at the upcoming ESS, where a wide range of researchers will be able to gain access the prototype.

This prototype in turn will then be both used for dissemination, where the scientific community can be made aware of the concept and the outstanding research possible at high-flux neutron sources that are used to capacity by the SoNDe detector concept, and as a template for potential other users that may want to use the SoNDe detector concept either when building their neutron research facilities of when updating them. The issues connected with the dissemination of intellectual property will be kept in mind at all stages of the development.

Finally, locations of future instruments or instruments to be upgraded will be identified so these facilities can benefit from the SoNDe detector concept. Here the estimation of budget for future construction of further detectors using the SoNDe concept will be instrumental to help future users and decision makers plan neutron research facilities.

Sex/Gender Analysis

The checklist as laid out in the Gendered Innovation project of L. Schiebinger and J.L. Hinds, co financed by the European Commission and the U.S. National Science Foundation has been checked A-D [18]. No potential sex/gender issues where identified.

Standards in personal management implemented with all participants guarantee gender-equality regarding human resources. These include, but are not limited to, assuring non-discriminatory hiring policies by appropriate committees. Within the FZJ there is an Office for Equal Opportunities (Büro für Chancengleichheit) that will support the Project Coordination to maintain a high standard of equal opportunity employment throughout the consortium. An equal opportunity officer is also installed in the FZJ administration to support the Project Coordination in that respect.

1.4 *Ambition*

State of the Art

Today’s large area neutron detectors focus mainly on three concepts:

1. Gaseous detectors with neutron converters
2. Scintillation detectors with photomultipliers
3. ^{3}He detectors

Schematics of all techniques are shown in Fig. 5 to Fig. 7. All techniques feature spatial resolutions between 5x5 mm^2 and 10x10 mm^2. State of the art counting frequency reaches from several 100 kHz (scintillation) to about 1 MHz (^{3}He).

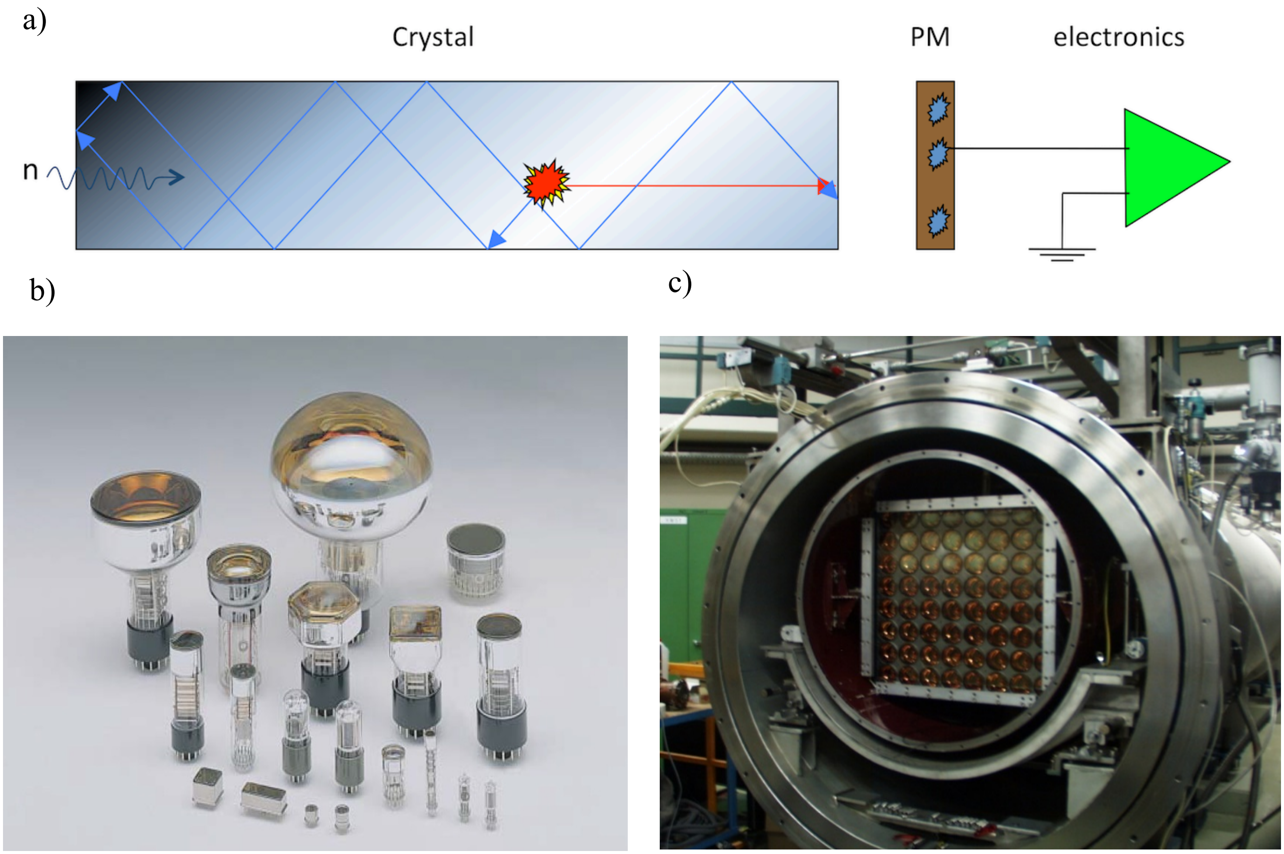

Fig. 5 a) Working principle and components of a scintillation detector. The neutron enters the conversion material, here a crystal, from the left, excites a light-flash which is in turn detected by the photomultiplier and counted by the electronics. b) Various examples for commercially available photomultipliers. The leftmost has a diameter of approximately 10 cm [17]. c) Current scintillation detector in a SANS instrument, about 1x1 m^2 in size. The photomultipliers are mounted in a rack, in front of this rack the conversion material will be mounted.

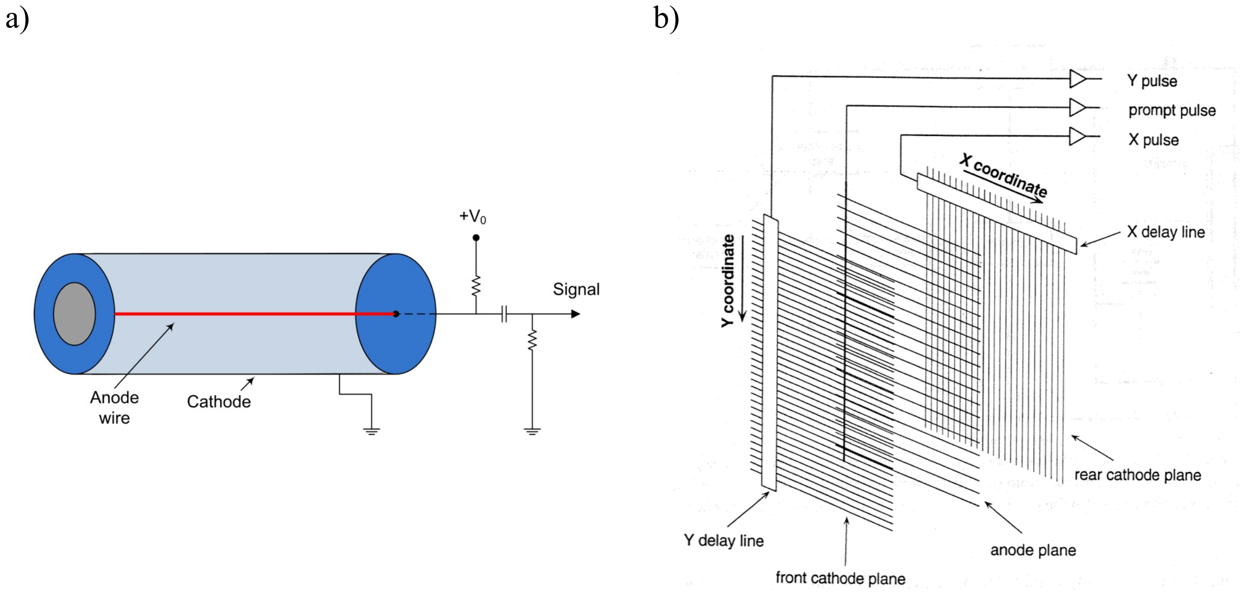

Fig. 6 Sketch of a) a gas detection tube and b) a position sensitive proportional detector [19]. In a ^{3}He setup the wires can also be in single tubes mounted onto a frame as in a). The discharge caused by a counting event blocks the complete detector (or a single tube) until the detection process is complete. A repair requires the dismantling of the complete detector or at least a dismantling in large parts.

For the scintillation converter detectors the dead time of the scintillation material is usually negligible however the dead time of the photomultipliers in current setups is substantial (maximum counting rate per photomultiplier is in the kHz range). This is coupled with the fact, that current photomultipliers cover an area of about 5x5 cm^2 at the detector behind the scintillation material (see Fig. 5). To improve the resolution to usable values around 8x8 mm^2 the Anger principle is used, where the exact position of a scintillation event is triangulated using a square array of photomultipliers (see Fig. 7). This means, that for the dead time of a photomultiplier the complete 3x3 array cannot detect any further neutron events. Additionally, there is a quite large dead area between the single PMTs, due to geometric boundary conditions (round PMTs) and because the evacuated glass vessel cannot be made very thin in order not to break when evacuated.

In case of the gas decay detectors the horizontal resolution is determined by the thickness and distance between the individual gas tubes and the vertical resolution by the detection of the location of the decay event along the wire (see Fig. 6 a). Here the complete length of a tube cannot be used for the dead-time once a single neutron event occurred anywhere along the tube. This prevents extremely high counting frequencies, as the complete height of a detector along a tube is essentially blocked during the dead-time of this tube and all neutron events in this area during the dead-time are lost.

While the restrictions above concern the resolution and counting frequency, there are drawbacks in maintenance and repair common to both concepts. The gas decay detectors are either single tubes connected to a carrying frame or tubes milled into a monolithic block. In both cases the detector has to be removed from the instrument completely to perform a refilling in case of a gas loss or to insert new wires in case of a ruptured wire. This is further complicated by the fact that most gas decay detectors work with ^{3}He, which is rare and needs to be procured before repairs can be begin. The scintillation converter detectors can be repaired by changing the photomultipliers and the corresponding electronics. Here afterwards a new calibration has to be done, which not only affects the changed photomultiplier but also the other photomultipliers used in the same array for the Anger interpolation. These effects often lead to downtimes of a few months, which nowadays at reactor-

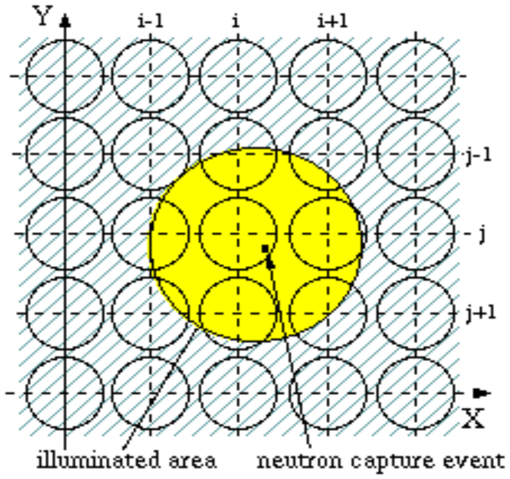

Fig. 3 Sketch of the working principle of an Anger-Camera. The centre of the neutron event, i.e. the exact location on the detector is determined by crosstalk signal to neighbouring photomultipliers. While this increases the resolution it simultaneously decreases the maximum count-rate drastically, as for the detection of each event 3x3 photomultipliers are necessary, which are blind to additional neutron events during that time, resulting in a drop in counting rate by a factor of 9.

based sources can be placed in the phases without reactor operation. However, spallation sources potentially can run continuously or with very short breaks that do not allow for extended periods when repairs or maintenance are due.

There are also detectors with higher resolutions available (Si-based CCD, Gas Electron Multiplier (GEM)), however these high-resolution detectors are also not capable of using a high-flux source to capacity. In the case of Si-based CCDs, the time resolution is inappropriate for application at spallation sources, where timing is required for the application of time-of-flight methods to determine neutron energy. Radiation softness is also an issue. For GEM detectors, the detection efficiency is limited to a few percent, or the resolution degrades significantly due to the amount of scattering material affecting the path of the neutrons.

Innovation Potential

As laid out in the previous section there are four main points to be improved upon to make detectors capable of operating at a high-flux neutron source and use its flux to maximum capacity:

1. Limitation for high-flux usage
2. Large area with a simultaneous high resolution
3. Avoiding rare components, such as ^{3}He
4. Ease of maintenance and repair

Single components of the SoNDe detector concept may be patent protected (e.g. the multi-anode photomultiplier chips). The other components will have to be developed and a preliminary patent research did not reveal any competing intellectual property. However, during the development of new components the inclusion of patent protected technology may become necessary or at least sensible.

The patent research to determine the landscape of knowledge revealed three relevant patents, two of which (US2003178574(A1) and US2010019160(A1)) do not compete, as they describe a different approach to neutron detection by scintillation and one of which describes the MaPMT that is a candidate for the optical detection of the photons from the converted neutrons (DE112012004387T5). This last patent affects a component of the prototype, however the MaPMT are supposed to be bought anyway. For this patent research the Derwent Innovations Index database with the patent classification G01T-003/06 was used. The FZJ patent department of the FZJ central library assisted the patent research.

Future Infradev calls, especially for the development of large scale neutron research facilities, will be able to draw on the development of the SoNDe project in order to have a neutron detection technique, fulfilling a wide range of requirements of the neutron scattering community, readily available. This is especially true for the ESS, which has been prioritised in the ESFRI roadmap.

The chip based counting electronics will be developed during the project. This will help keeping know-how and capability to manufacture these electronic components available in Europe. Moreover, a close connection between development, integration and application is desirable, especially in highly specialised electronics, as short distances facilitate feedback between application, manufacturing and development. Also, developing integrated counting electronics for fast detection events on a single chip is at this point a relevant innovation to a lot of fields of application, for example, aside from neutron detection, to PET application for medical diagnosis.

As already mentioned, for future Infradev projects, concerning neutron research, a ^{3}He independence of the detector technology is desirable as it allows the planning and construction of neutron research facilities in Europe without having to rely on external suppliers of ^{3}He.

2. Impact

2.1 Expected impacts

To give a sound decision basis for future large-scale neutron scattering facilities large area neutron detectors have to be (1) capable of working on the future high-flux neutron sources, (2) independent of ^{3}He as an increasingly rare resource as not to impede construction and operation of these facilities and (3) capable of high time-resolution to allow for instruments to run in TOF mode. These facilities are of global interest for a wide range of scientific fields ranging from archaeology to medical studies for drug development (see Fig. 1) [5]. As planning, design and construction of these facilities take place on a time-scale of decades, a continuous development of key technologies, such as the SoNDe detector concept, is of paramount importance to create roadmaps for the development of the European neutron scattering large-scale facilities for years to come.

The technical work that will be carried out in the SoNDe project will strengthen the European Research Area by supplying it with a high-flux capable neutron detection technology with a high spatial resolution. Only with detectors that are able to stand the high-flux of the upcoming neutron sources these can be used to full capacity and thus create their maximum scientific impact, as only with these high effectiveness, scientific performance and attractiveness of the European research area can be maintained within the neutron research community. Also the technological development capacity, not only of neutron research facilities, but also of depending fields in chemistry, biology, medicine, engineering and information technology, will be strongly dependent on the capacity of performing high quality neutron experiments. This demands for a strong and reliable detector concept such as SoNDe.

Aside from the huge scientific impact it is also important to note that keeping capabilities and know-how for the development of high-tech components for such a detector in Europe is a key issue regarding technological independence. Moreover, the close proximity between manufacturing and the final application and users benefits both, as this allows for a fast implementation of improvements based on the feedback from application of the components. Training and mobility of early-stage individuals in high-profile and in-demand techniques are also an expected impact of this project.

Throughout the project alternative applications of the developed technologies will be considered, such as PET. This also includes keeping in mind innovation potential in other areas than neutron detection technology, which will be assessed in meetings on a regular basis.

2.2 Measures to maximise impact

a) Dissemination and exploitation of results

Dissemination of results will include the publication of articles in accepted, peer-reviewed scientific journals appropriate for the development of detector concepts. Additional measures will be the presentation of the obtained results at international scientific conferences, which will not only make the community, which is actually involved in the development of detectors and instruments aware of the results, but also the instrument users, who will ultimately use the detector at a neutron scattering instrument. These users will also finally be able to exploit the full advantages given by the SoNDe detector concept in their experiments and thus be able to gain high quality results for their respective research, which will span over fields such as chemistry, biology, food science, engineering and information technology.

A webpage documenting progress and activities during the course of the project and collecting published materials will also improve dissemination.

In the early stage of the project (deliverable 5.5) a workshop will help finding additional users and possible other applications aside from neutron detection (such as PET, others may turn up). Contributions from this workshop in turn will help addressing the communities needs from an early stage on. At the completion of the project also a report about financial and legal feasibility will be published as a guideline for users (deliverable 5.7).

In terms of marketing, respectively the access to the intellectual property necessary to built detectors using the SoNDe concept, we plan making the necessary knowledge public by patent publications, as well as advising and supporting others using the concept.

As for a technology whose main application will be in large scale neutron facility there is only a limited market, where all potential users will be made aware of the availability of the technology. This will be achieved by all the above-mentioned points, which are well-established dissemination concepts within this area of research. Different techniques with applications in other fields will be promoted appropriately if identified during the course of the project, and identification of these possible applications will continuously be encouraged throughout the project.

At this point, the consortium members have not yet decided whether to deliver a complete setup, its components or the necessary intellectual property to the market. All these options are widely accepted in the neutron scattering community. This will be decided during the course of the project, based on the experiences made at that time. The same rational applies to all components developed within the framework of the project, which may have applications of their own outside neutron research.

To account for this the initial meeting of the project will also include a section, where the **awareness of all participants towards IPR** will be raised. Each subsequent semi-annual meeting will in turn also include a **harvesting section**, where the participants collect possible innovations and agree on an IP management procedure. For this an IP-specialist will be present at these meetings.

The FZJ has already a wide experience in holding summer schools for young researchers, which may also be interesting for technicians in the research area. At these workshops the new detector concept can be shown to a young generation of researchers and thus make them familiar with the concept at an early stage. Moreover, close collaboration with universities (such as the TU München, University of Munich or the RWTH Aachen) will allow presenting the concept to students early in their career.

The measures mentioned above will nurture visibility of the concept in the addressed community, which is in itself the expected impact of the proposed project. As the SoNDe detector concept will resolve a variety of issues discussed in the neutron research community (high-flux, ^{3}He shortage and reliable operation) this will lead to the adaption of the concept in European research facilities, either to be built or to be updated in the future.

Additionally to these conventional dissemination measures, a mutual benefit will come from the contribution of the SoNDe detector concept to the compliance standard about data acquisition, which is to be developed at the ESS. As a detector that is developed along with one of the major neutron facilities during its planning and construction stage it will be one of the models for future designs to rely on.

The appropriate structure of the consortium to support exploitation is addressed in section 3.3, *Consortium as a whole*. This structure will also be aimed to manage the ownership and access to key knowledge (IPR, data etc.) in a way to ensure maximum exploitation by any number of parties who want to use the SoNDe detector concept. The IPR management will be addressed in a separate consortia agreement.

This project will try and maintain the gold standard of open access wherever possible, i.e. free access to all results. This will be achieved by using the appropriate journals and patents. As for the journals, there can either be the possibility to publish in a peer-reviewed journal that offers open-access by itself or allows a simultaneous publication in open web-archives, such as arXiv.com, or a combination thereof. Patents are open-access by definition, so they will also meet the gold standard of open-access.

Concerning data availability and storage at the moment there is a policy of keeping all records available for at least ten years at the FZJ, which will also be applied to this project by all partners.

b) Communication activities

Results of the project's research will be continuously published during the course of the project in peer-reviewed, scientific journals. Moreover all members of the consortium will be encouraged to present results on international conferences as conference contributions. These contributions will in turn be available to the neutron scattering community, which then can update existing neutron scattering instruments or include these into future designs.

The building and upgrade of high-performance neutron scattering instruments will also disseminate among the complete community of researchers using neutrons, who cover a wide variety of fields, such as archaeology, chemistry, biology, medicine, engineering and information technology. At this point it is impossible to pinpoint secondary impact by their research as they cover such a wide range of fields, which may have an impact on any aspect of every-day live and society.

The communication activities as detailed in the above paragraph are in specifically

- Peer-reviewed journals (preferably open-access gold standard)
- Conference presentations and proceedings
- Creating a webpage covering progress and published material of the project
- Workshops for users
- Summer schools for students as future users

3. Implementation

3.1 Work plan — Work packages, deliverables and milestones

The overall structure of the work plan will include five workpackages

1. **Prestudies:** Identification and testing of appropriate technologies and materials needed to build a high-flux capable neutron detector as laid out in the objectives section. This testing will be performed creating a 1x1 technical demonstrator.
2. **Demonstrator:** Creating the technical plan to build a detector meeting the criteria set out in the objectives section, based on the experiences of a 2x2 technical demonstrator.
3. **Upscaling:** Creating a working prototype as a technical demonstrator, that will also identify any issues connected with the actual construction of such a detector and thereby gaining the necessary knowledge to build and support a detector of the SoNDe concept in the future.
4. **Large-Scale Construction:** Final testing and publishing of the results of the large-scale prototype.
5. **Management and dissemination.** Here two types of deliverables are possible either touching management or dissemination.

The detailed timing, including necessary sub steps will be detailed in the Gantt chart for the work packages (Fig. 8). Here it should be noted that building a technical demonstrator is instrumental to achieve the expected impact and the ensuing dissemination, as a demonstrator in a real working environment is an irrefutable proof of the feasibility of the concept and thus will help convincing the community to accept the SoNDe detector concept on a wide basis.

Detailed time planning is shown in the Gantt chart in Fig. 8. Even though some packages may be dependent on each other the start of a dependent workpackage does not necessarily need to wait for the completion of the prior package, given there are already some results that can be used to start working on the depending package. Overall project time is estimated to be four years, however this will require full personal effort on each subproject to be completed in time.

Each of these workpackages, except the Management and Dissemination workpackage, will lead to the achievement of a milestone:

1. Concept verification: By building and assessing a 1x1 technology demonstrator, the overall feasibility of the technology will be assessed.

2. Concept validation: By building and assessing a 2x2 prototype the potential to construct a complete detector from the single segments will be shown.
3. Ready to build a large-scale prototype: Evaluation of the experiences during the construction of the technology demonstrator and the small-scale prototype will enable us to construct a large-scale prototype.
4. Large-scale prototype complete: The construction of the large-scale prototype will show the feasibility of the technology and give a working model for demonstration and dissemination.

A list of the necessary deliverables is:

- Building a 1x1 segment hardware demonstrator to show the feasibility
- Writing an internal report for the research on the material feasibility of the aforementioned demonstrator and publish the results in a peer-reviewed journal
- Assessing the radiation hardness of the counting electronics and prepare an internal report
- Building a 2x2 segment hardware demonstrator to test for the scalability of the technology
- Testing and evaluating the 2x2 demonstrator and publish the results in a peer-reviewed journal
- Preparing an internal report on the electronics of the 2x2 demonstrator
- Preparing an internal report on the mechanical issues of the 2x2 demonstrator
- Preparing an internal report about issues regarding large scale system integration of the 2x2 demonstrator
- Constructing a large-scale prototype (1x1 m^2)
- Publishing a paper about the large-scale prototype in a peer-reviewed journal
- Perform semi-annual meetings to assess the progress at the different project stages. These meetings will also give the possibility to adjust the work plan to unforeseen issues and be used as a possibility to assess potential IP issues (harvesting meetings).
- Publish results as conference proceedings and conference contributions.
- Finding additional applications for the proposed concept or the developed innovations or parts thereof
- Performing an audit half a year before the end of the project, to assess the success of the project
- Holding a workshop for potential users to identify applications for the innovations and find potential sites for detectors employing the SoNDe concept
- Creating a website that reports on the project’s results and progress
- Perform market research and financial planning for potential users. This way we want to find potential users, draft a financial concept for purchasing products that may come out of the project (services, hardware, IP) and compare to current technology also in terms of financial feasibility
- Create financial and progress reports to European Commission.

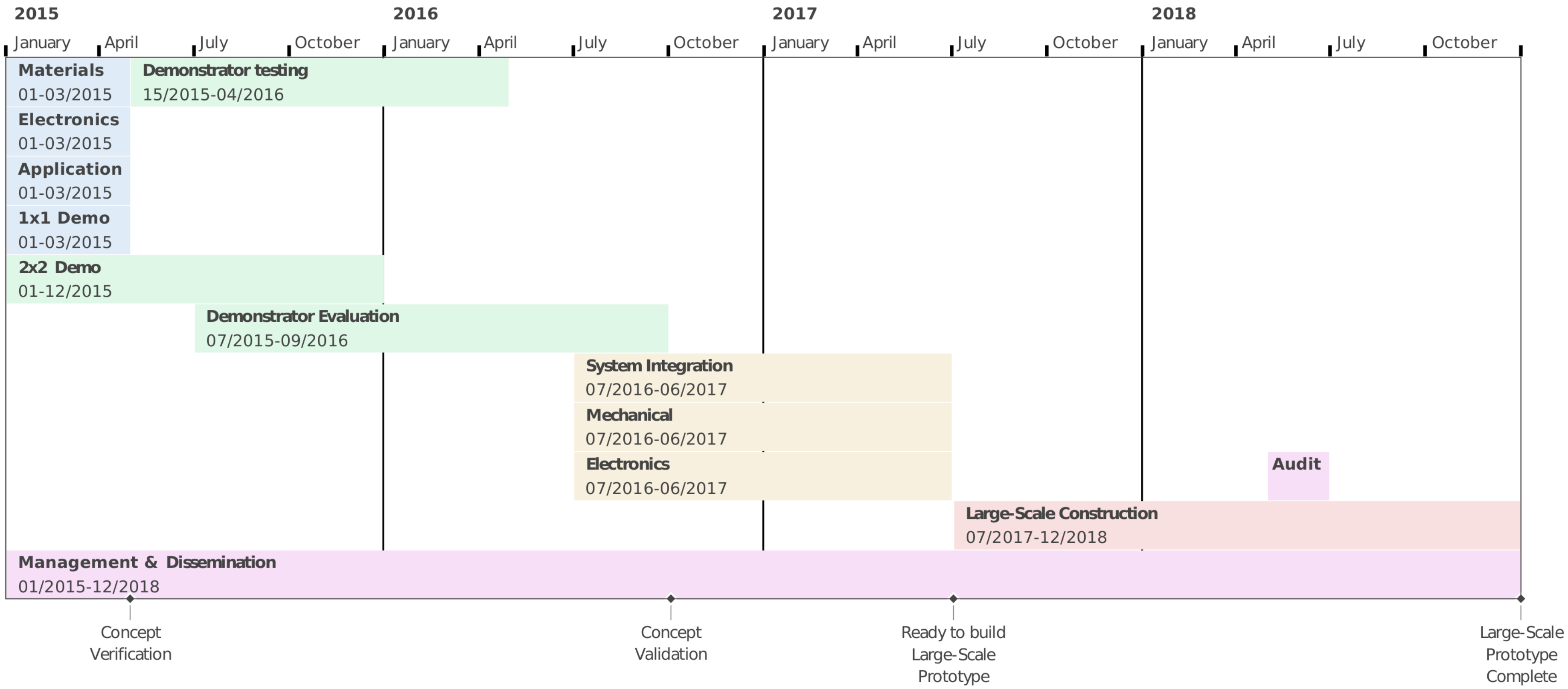

Fig. 4. Gantt chart, detailing the different work packages and their components. Dissemination as a continuous process consists of several deliverables. The milestones are listed on the bottom of the timeline. Work packages are colour coded by prestudies (blue), demonstrator (green), upscaling (vanilla), large-scale construction (red) and Management and Dissemination (purple).

3.2 Management structure and procedures

The organizational structure (see Fig. 9) of the SoNDe project will assign specific tasks to each partner, make sure there is a control over the progress of the projects over time and include a risk management protocol.

It is the principal aim of the management structures to render support to each member of the consortium as needed, coordinate the efforts of all participants in the best way possible as well as to provide financial and progress accounting toward the European Commission.

The general organizational structure will put FZ Jülich in charge of the overall project management and engineering, LLB in charge of testing and evaluating and the ESS will deal with integrating mechanisms to integrate the detector into large scale facilities in terms of meeting large scale facility policies regarding software, power supply and necessary access to local workshops. Lund University and ESS will share responsibilities in most areas due to a well-established cooperation between these two entities in a wide range of areas. While FZ Jülich is taking a large part in the overall engineering effort, the development of the counting electronics will be handled by IDEAS.

The steering committee, consisting of the directors of the contributing institutes and the IDEAS CEO, meets annually. Additional meeting can be convened at the request of at least one partner. The steering committee will support the project coordination and make major strategic decisions during the course of the project. The project coordination in turn will report to the steering committee during their annual meeting.

The project coordination will receive reports from the workpackage responsibles at the semi-annual meetings. As is the case for the steering committee additional meetings can be convened at the request of either at least one workpackage responsible or the project coordination. The project coordination is coordinating the efforts of the single workpackages and makes operative decisions to ensure the meeting of the project objectives as a whole, as well as support all workpackage responsibles in meeting the deliverables for their workpackages.

As each of the workpackages is of non-negligible complexity, day-to-day decisions will be made at the lowest level, regarding the assigned tasks. This will allow for a continuous control over progress and problems in each workpackage. If deliverables in a workpackage are endangered the workpackage responsible will be notified and further escalate the problem if needed and the consortium members will work in a joint effort to keep the workpackage in time.

Here it is important to note that the workpackage Management and Dissemination has two branches of deliverables. This was agreed upon by all participants as decisions and the results of deliverables in the management area immediately feed back into the dissemination part and vice versa, especially in the case of IP issues where decisions on dissemination are linked with exploitation decisions of the IP. Due to this intimate relation between the two branches this workpackage was not broken down into two distinct workpackages.

Major risks in the project are laid out in Table 3.2 b). The Project Coordination and the corresponding workpackage responsibles will permanently observe any of these risks, take appropriate action if needed and further escalate it to the steering committee if necessary, in order to assure any of these risks is addressed in a state as early as possible. They will also coordinate the joint effort of all partners to resolve any resulting issues.

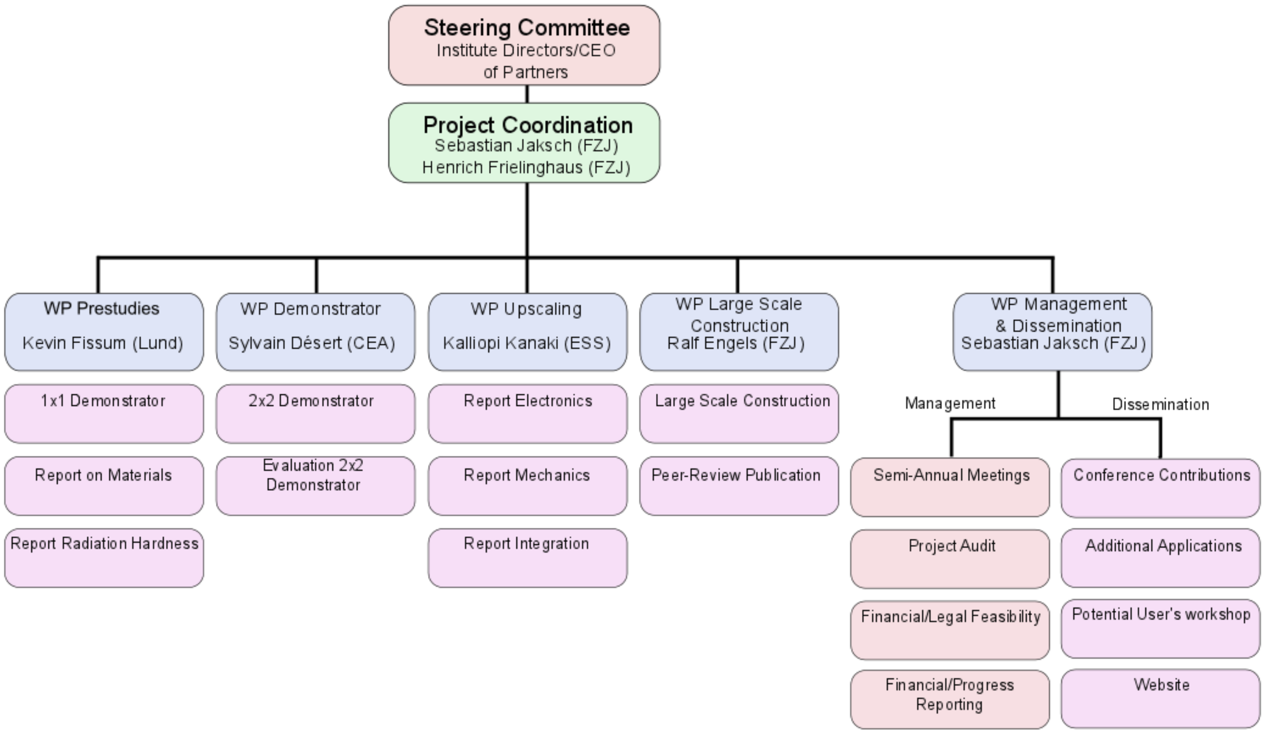

Fig. 9. Organisation chart of the management structure of the SoNDe project. Strategic decisions will be made by the steering committee (top red). The Project Coordination (top green) reports to the steering committee on a regular basis and manages operative decisions during the project. Each workpackage responsible (blue) reports to the Project Coordination at the semi-annual meetings or at appropriate times, when additional meetings are necessary. They coordinate the deliveries (pink and lilac) in their workpackage, while day-to-day decisions are made in the single deliveries.

After completion of each workpackage, there will be joint evaluation meetings (semi-annual) where the output of the completed workpackage into the following workpackages is evaluated and necessary adaptions the following workpackages, depending on the results, will be discussed. The first of these semi-annual meetings will also be used as an **awareness-raising** meeting regarding IP, the later meetings will take innovation management (**harvesting meetings**). On the basis of these discussions, which will include an expert for IP, it will be decided which way of dissemination is appropriate for the achieved results (peer review journal, patent, conference presentation…).

3.3 Consortium as a whole

The consortium consists of the Forschungszentrum Jülich, the Laboratoire Léon-Brillouin, the European Spallation Source, Lund University and IDEAS as an industrial partner.

The Forschungszentrum Jülich has the capability and a proven track record of completing engineering tasks of high complexity, such as the design of the SoNDe detector concept.

At the LLB there is a facility (TPA spectrometer) capable of producing high-resolution neutron scattering images, needed to test the required high resolution of the detector. Simultaneously the test for high-flux capability can be performed there, by using the primary beam of the instrument. Also an irradiation station at the LLB is available. This irradiation station does not allow for the detailed testing as a dedicated instrument would, but for a range of the testing only a high flux of neutrons is required. This simpler instrument can also help avoid proposal structures, as it is less requested by other users.

The ESS is a large-scale neutron facility to be built in Sweden. As such, it is ideally suited for developing the concept of integrating detectors built using the SoNDe concept in these facilities in terms of engineering support needed on site and meeting software policies of large-scale facilities. Close cooperation with Lund university ensures a close connection to the scientific community as well as the possibility of introducing students at an early stage in their career to this high-profile research facility.

Substantial parts of the counting electronics will be developed and manufactured by IDEAS as a full **industrial partner** in this project. Together with the other consortium members they will create a requirement catalogue for the electronics and design the electronics accordingly.

Thus, development, integration, testing and evaluation as well as final built are represented by one or more members of the consortium. Continuous internal communication and meetings on a semi-annual basis will ensure all partners are informed about the progress at the different workpackages and can render additional support to each other if needed. This separation of responsibilities with the option for mutual support will ensure an effective working environment. Intellectual property issues are addressed in the consortium agreement.

Even though the SoNDe detector concept is a scientific project with little applicability outside neutron science (which, however, in itself is very versatile with a wide range of potential users and applications) the dissemination and of the concept is a central issue in case of an infrastructure project such as SoNDe. IPR management issues will be addressed by the consortium agreement and by the reports of the semi-annual meetings (**harvesting meetings**). Financial feasibility and comparisons with contemporary detector concepts will be evaluated throughout the project.

This policy towards IPR management also guarantees the the industrial partner IDEAS will be put into a position to deliver services and or hardware to users, which are based on the results of the research and development done in this project. Details regarding property of IP will be detailed in the consortial agreement. This also guarantees the possibility for commercial involvement and exploitation.

Exchange Programme

During the course of the project there will be an exchange of scientists and/or engineer between the different centres to nurture international collaboration. For this purpose at least 12 person/month of work will be carried out by an ESS engineer on site at the FZJ. This does not preclude additional exchange programmes within the project, which are thoroughly encouraged.

Industrial Cooperation

While at the moment IDEAS is the only industrial partner in this project the complete process of development and production will take place within the consortium. The non-industrial partners by nature will not be able to produce detectors applying the SoNDe technology to an array of users, or even be able to deliver parts to users with different fields of application of technology developed during the project, as they are scientific institutions. The plan for proliferation of the technique as detailed in the financial and legal feasibility report (deliverable 5.7) will thus also include industrial cooperation with partners besides IDEAS, which are able to deliver those parts of the project that cannot be delivered by IDEAS.

Financial Requirements

This project exceeds the recommended sum of 3 M€ for a research and innovation action in the framework of Infradev-1 / Horizon2020. This is due to both the material and personnel effort needed when developing a completely new detector. While personnel cost amounts to roughly 1.4 M€ the material costs detailed in Table 1 amount to about 50 % of the project budget with 1.6 M€. The cost for the material however cannot be reduced while maintaining the goal of developing a detector with outstanding performance, both in high-flux capability and resolution. The personnel costs, amounting to 188 person/month cover 4 full-time positions for the 4-year duration of the project (188/(4*12) ≈ 4). Considering the amount of work to be done both in technological development, testing and finally construction this amount of work is required. The added 25 % for indirect costs thus raise the complete requested grant to just below 4 M€.

We therefore think the overall budget is reasonable for a project of this size with the objective of developing a new neutron detection technique.

Table 1 Projected material costs for construction of a large-scale detector using the SoNDe technique.

Material	Price (Euro)
Housing for the detector	30000.00
Converter Material (^{6}Li or ^{10}B), 1 x 1 m^{2}	200000.00
400 MaPMT, 2150.00 € each	860000.00
Counting electronics (400 boards, approximately 1000 € each)	400000.00
Additional supplies (computers, cables, …)	30000.00
Total	1600000.00

3.4 Resources to be committed

Table 3.1a: Work package description

For each work package:

1			**Start Date or Starting Event**				1/2015
Prestudies							
Participant number							
Short name of participant	FZJ	LLB	ESS	Lund	IDEAS		
Person/months per participant:	3	0.5	0.5	0.5	1		

Objectives

Perform the prestudies of materials needed, here specifically:

-electronics

-application identification

-building a 1x1 demonstrator

Description of work

In this WP prestudies will be performed, including:
-eletronics
-identification of potential applications. This also includes applications that are not covered by the initial science case, such as PET detectors
-a technical demonstrator made up from a single module will be built

Deliverables (brief description and month of delivery)

1. Hardware of the 1x1 single module technical demonstrator, delivery 04/2015
2. Studies report on materials internal report and publication, delivery 04/2015
3. Report on radiation hardness of electronics, delivery 04/2015

2			**Start Date or Starting Event**				1/2015
Demonstrator							
Participant number							
Short name of participant	FZJ	LLB	ESS	Lund	IDEAS		
Person/months per participant:	27	6	4	2.5	12		

Objectives

-construction of a 2x2 demonstrator

-testing of said demonstrator

-evaluation of this tests

Description of work

In this WP focus will be on the construction of a technical demonstrator of 2x2 segments.
This comprises construction, testing and evaluation of the tests of this demonstrator. By this we will learn, after having a working neutron detector as such in a 1x1 demonstrator, if this concept scales and where the challenges concerning the connection of several modules are.

Deliverables (brief description and month of delivery)

1. construction of a 2x2 demonstrator, delivery 01/2016
2. evaluation of tests of 2x2 demonstrator, delivery 07/2016

3			**Start Date or Starting Event**				7/2016
Upscaling							
Participant number							
Short name of participant	FZJ	LLB	ESS	Lund	IDEAS		
Person/months per participant:	24	3	8	2	9		

Objectives

enable the upscaling of:
-eletronics (heat issues, electrical specifications)
-mechanics (high packing density)
-system integration (software, eletrical compatibility)

Description of work

This workpackage will solely concern with the challenges connected with upscaling the technology. This includes issues with the counting electronics (such as heat development, maximum current possible, necessary amplifiers), mechanical construction (reaching the highest possible packing, i.e. the least possible dead space) and system integration (introducing a detector in a large scale facility, such as ESS)

Deliverables (brief description and month of delivery)

1. Internal report on upscaling of electronics, delivery 01/2017
2. Internal report on mechanical issues before upscaling, delivery 01/2017
3. Internal report on systems integration with ESS, delivery 01/2017

4		**Start Date or Starting Event**				7/2017	
Large Scale Construction							
Participant number							
Short name of participant	FZJ	LLB	ESS	Lund	IDEAS		
Person/months per participant:	30	3	5	2	6		

Objectives

Create a large-scale (100cmx100cm) detector prototype.

Description of work

In this final stage of the project a large scale detector prototype will be built. This is to be used to demonstrate to the community the feasibility of the concept in a working environment at a large-scale facility, such as the ESS, as pointed out in the prioritization of the ESFRI roadmap.

Deliverables (brief description and month of delivery)

1. Construction of a large scale detector (100x100 cm^2), delivery 12/2017
2. Peer reviewed publication of large-scale detector, delivery 12/2017

5			**Start Date or Starting Event**				1/2015
Management and Dissemination							
Participant number							
Short name of participant	FZJ	LLB	ESS	Lund	IDEAS		
Person/months per participant:	30	3	2.5	0.5	3		

Objectives

Over the whole running time there will be a need for management and coordination of
-cooperation between the partners
-dissemination of the results
-control of reaching the deliverables of the different workpackages/quality control

Description of work

This workpackage will concern with management and coordination of the partners and the dissemination. This may include organizing the necessary meetings, organizing workshops for the user community of the detector, preparation of quality control, preparation of publications of any form, IPR management. The first meeting semi-annual will be also be used to increase **awareness for IPR** issues, each subsequent meeting will also be a **harvesting meeting**, where measures as to how to publish data (patent or peer reviewed or a combination thereof) will be discussed.

Deliverables (brief description and month of delivery)

1. Semi annual meetings for internal assessment and publication procedure
2. Conference Proceedings at major conferences concerning neutron instrumentation and detector development
3. Finding additional potential applications of innovations, delivery 07/2015
4. Preparing and performing an audit for project evaluations, delivery 07/2017
5. Preparing and holding a workshop for potential future users, delivery 01/2016
6. Publishing website with details on project and project progress
7. Financial/Legal feasibility report
8. Financial/Progress report to European Commission

Table 3.1b: List of work packages

Work package No	Work Package Title	Lead Participant No	Lead Participant Short Name	Person-Months	Start Month	End month
1	Prestudies	Lund		5.5	01/2015	05/2015
2	Demonstrator	LLB		51.5	01/2015	10/2016
3	Upscaling	ESS		46	07/2016	07/2017
4	Large-scale construction	FZJ		46	07/2017	12/2018
5	Management and Dissemination	FZJ		39	01/2015	12/2018
				188		

Table 3.1c: List of Deliverables[1]

Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date
1.1	Hardware (1x1)	1		DEM	CO	5
1.2	Material prestudies report	1		R+DEC	CP+PU	5
1.3	Electronics report on radiation hardness	1		R	CO	5
2.1	Hardware (2x2)	2		DEM	CO	13
2.2	Test and evaluation of deliverable	2		R+DEC	PU	23

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[1] If your action taking part in the Pilot on Open Research Data, you must include a data management plan as a distinct deliverable within the first 6 months of the project. This deliverable will evolve during the lifetime of the project in order to present the status of the project's reflections on data management. A template for such a plan is available on the Participant Portal (Guide on Data Management).

	2.1					
3.1	Report on electronics	3		R	CO	31
3.2	Report on mechanics	3		R	CO	31
3.3	Report on system integration	3		R	CO	31
4.1	Construction Large Scale	4		DEM	CO	48
4.2	Paper on Prototype	4		R	PU	48
5.1	Semi Annual Meetings	5		R	CO	Each half year
5.2	Conference Proceedings	5		R+DEC	PU	At major conferences on detector and instrument development
5.3	Finding additional applications	5		R	CO	7
5.4	Audit	5		R+DEC	CO	43
5.5	Giving a workshop for potential users	5		DEC	PU	13
5.6	Website	5		DEC	PU	1
5.7	Financial/Legal feasibility report	5		R	PU	48
5.8	Financial/Progress Report	5		R	CO	Quarterly/Annual Reports

Table 3.2a: List of milestones

Milestone number	Milestone name	Related work package(s)	Estimated date	Means of verification
1	Concept verification	Prestudies	5	Internal report / hardware / publication
2	Concept validation	Demonstrator	22	Internal report / hardware / publication
3	Ready to built large scale prototype	Upscaling	31	Internal report
4	Large scale prototype complete	Construction	48	Hardware / publication

Table 3.2b: Critical risks for implementation

Description of risk	Work package(s) involved	Proposed risk-mitigation measures
Beamtime availability	All	Exchange of testing site from LLB to MLZ or vice versa. Additionally the irradiation station at the LLB may be used for a number of tests.
Radiation hardness of components	1 and 2	Adapt shielding. As a second measure the used ASICs may be modified.
Crosstalk between the pixels	1 and 2	Adaption of the grooving between the pixels. Also additional light-guides can be included in the conversion material.
Schedule and budget	All	As a prototype, it is feasible not to equip all available slots with detector modules. These can be added at a later time and still the technical feasibility can be shown
Heat development of components	1 and 2	Improve cooling (air → water), adapt cooling design

Table 3.4a: Summary of staff effort

Please indicate the number of person/months over the whole duration of the planned work, for each work package, for each participant. Identify the work-package leader for each WP by showing the relevant person-month figure in bold.

	WP 1	**WP 2**	**WP 3**	**WP 4**	**WP 5**	**Total Person/Month per Participant**
FZJ	3	27	24	**30**	**30**	114
ESS	0.5	4	**8**	5	2.5	20
Lund	**0.5**	2.5	2	2	0.5	7.5
LLB	0.5	**3**	6	3	3	15.5
IDEAS	1	12	9	6	3	31
Total Person/Months	5.5	51.5	46	46	39	188

Table 3.4b: 'Other direct cost' items (travel, equipment, other goods and services, large research infrastructure)

Please complete the table below for each participant if the sum of the costs for' travel', 'equipment', and 'goods and services' exceeds 15% of the personnel costs for that participant (according to the budget table in section 3 of the proposal administrative forms).

1 (FZJ)	**Cost (€)**	**Justification**
Travel	-	
Equipment	-	
Other goods and services	1600000	Materials necessary to manufacture the prototype, detailed list available
Total	1600000	

1 (FZJ)	**Cost (€)**	**Justification**
Travel	28500	Three travels per year and person
Equipment	-	
Other goods and services	-	
Total	28500	

1 (FZJ)	**Cost (€)**	**Justification**
Travel	-	
Equipment	-	
Other goods and services	10000	Holding an audit and initial workshop, creating and maintaining a website
Total	10000	

1 (LLB)	Cost (€)	Justification
Travel	3875	Three travels per year and person
Equipment	-	
Other goods and services	-	
Total	3875	

1 (LLB)	Cost (€)	Justification
Travel	-	
Equipment	-	
Other goods and services	5000	transport costs for transporting prototype for testing
Total	5000	

Please complete the table below for all participants that would like to declare costs of large research infrastructure under Article 6.2 of the General Model Agreement[2], irrespective of the percentage of personnel costs. Please indicate (in the justification) if the beneficiary's methodology for declaring the costs for large research infrastructure has already been positively assessed by the Commission.

CEA/LLB	Cost (€)	Justification
LLB	120000	Unit price for 20 days of beamtime (20 days per 6000 EUR) as a service in a large-scale facility (LLB)

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[2] Large research infrastructure means research infrastructure of a total value of at least EUR 20 million, for a beneficiary. More information and further guidance on the direct costing for the large research infrastructure is available in the H2020 Online Manual on the Participant Portal.

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List of Abbreviations

CCD	Charge-Coupled Device. Sensor technology for detection of light and/or particles
ESS	European Spallation Source, Lund, Sweden
GEM	Gas Electron Multiplier. Detection technique for particles.
ILL	Institut Laue-Langevin neutron research facility, Grenoble, France
ISIS	Pulsed neutron and muon source at the Rutherford Appleton Laboratory, Oxfordshire, UK
KWS	Kleinwinkelstreuung, German for small-angle scattering, see SANS
LLB	Laboratoire Léon-Brillouin, CEA institute, Paris, France
MaPMT	Multi Anode Photomultiplier
MLZ	Maier-Leibnitz Zentrum, neutron research facility, former FRMII, Garching, Germany
SANS	Small-angle neutron scattering, structure resolving neutron scattering technique, often used in material, condensed matter sciences and biological/medical studies
SKADI	Small K Advanced Diffractometer, an instrument proposal for a small-angle neutron scattering instrument at the ESS
TOF	Time-of-flight, in neutron scattering this refers to time stamping the single counting events