Executive Overview

Introduction: The evolving story

ESS, the European Spallation Source, will be a major user facility at which researchers from academia and industry will investigate scientific questions using neutron beams. Neutron methods provide insights about the molecular building blocks of matter not available by other means. They are used for both basic and applied research.

ESS will be a slow neutron source of unparalleled power and scientific performance. It will deliver its first protons to a solid, rotating tungsten target in 2019, which will in turn generate neutrons for delivery to an initial suite of seven neutron scattering research instruments. ESS will reach its full design specifications in 2025, with a suite of 22 research instruments. The publication of the Technical Design Report in 2013 represents an important milestone for the ESS project, marking its readiness to move forward with construction activities. This executive overview provides a brief summary of the key insights and findings of the Technical Design Report.

The road to achieve such a European high-power spallation source has been long and winding. The neutron itself was discovered in 1932 in Cambridge by James Chadwick. During the 1950s, research installations in the north American subcontinent developed the early instrumental techniques that used neutrons to unravel the atomic structures and dynamics of relatively simple materials. Cliff Shull and Bert Brockhouse received the Nobel prize in physics in 1994 for this work. A rapid rise in technical capabilities culminated, in the late 1960s, in the construction in Grenoble of a purpose-built high flux reactor source of slow neutrons. The Institut Laue-Langevin (ILL), as it was named, became the flagship of neutron research. In parallel, and with a somewhat different purpose, accelerator-driven sources of neutrons were also being developed. These facilities were excellent generators of fast neutrons that were used to compile a nuclear cross section database of all the elements and their isotopes in order to support the nuclear power industry. The early exemplars of such sources were based on electron linear accelerators, which, unfortunately, have significant background problems caused by the intense gamma radiation bursts that they generate.

In the late 1970s and early 1980s, scientists began to explore the use of proton-driven neutron sources, employing cyclotrons, synchrotrons or linear accelerators. Proton sources avoid the problems with gamma background from which electron sources suffer. Proton sources also hold a significant technological advantage over the most intense research reactors because the spallation reaction employed in proton machines generates significantly less heat per useful neutron than does a fission reactor. In addition, the generation of neutrons in pulses provides peak brightnesses that far exceed those available from reactors. ISIS, a proton spallation source that was powerful enough to challenge the supremacy of ILL, was built near Oxford in the late 1970s.

In 1998, the OECD research ministers endorsed a Megascience Forum report recommending that a megawatt-class spallation neutron source be built in each of the three developed regions of the world. Over the next five years, alternative configurations were studied. In 2003, following a plenary meeting of some 700 scientists and science policy-makers in Bonn, a new concept was put forward for ESS comprising a 5 MW proton linear accelerator delivering a 2 to 3 millisecond-long pulse to a single target station surrounded by a suite of 20 to 25 neutron instruments. This initiative held out the promise of neutron intensities that were a factor of six more intense, per megawatt of proton beam power, than contemporary existing or planned facilities. The user community in Europe endorsed this concept, and it has provided the framework for the ESS design process that is now nearing completion.

The decision to locate ESS near Lund was taken in Brussels on 28 May, 2009, after a competitive process
Parameter | Unit | Value
--- | --- | ---
Average beam power | MW | 5
Number of target stations | | 1
Number of instruments in construction budget | | 22
Number of beam ports | | 48
Number of moderators | | 2
Separation of ports | degrees | 5
Proton kinetic energy | GeV | 2.5
Average macro-pulse current | mA | 50
Macro-pulse length | ms | 2.86
Pulse repetition rate | Hz | 14
Maximum accelerating cavity surface field | MV/m | 40
Maximum linac length (without 100 m upgrade space) | m | 482.5
Annual operating period | h | 5000
Reliability | % | 95

Table 1: High level parameters, approved by the ESS Steering Committee on 18 April, 2011.

Neutron science and instruments

Neutron scattering techniques offer a unique combination of high sensitivity and high penetration as they monitor structure and motion at a molecular level. They address today’s cutting edge research questions, and will be even more important to meet tomorrow’s technological challenges. Their impact spans many scientific disciplines including physics, chemistry, biology, materials science, engineering and archaeology.

Neutrons can probe magnetism and superconductivity, guide the development of new materials, “look inside” an operating car engine, or illuminate an old master’s painting technique without damaging his priceless masterpiece. These techniques further industrial and technological progress, contributing to advances in fields ranging from pharmaceutical development to fuel cell technology. The neutron also holds promise of helping to unravel fundamental puzzles of the universe, such as why there is more matter than antimatter. Figure 1 illustrates the ability of neutrons to examine the internal structures of precious, irreplaceable materials (in this case, an Indonesian dagger sheath) without causing damage. The two images in Figure 2 exemplify the major contributions neutron techniques have made to understanding the magnetic properties of matter.

No single probe can cover the whole span of time and length scales that the various fields of science encompass. Techniques are often complementary rather than competitive even when their temporal and spatial scales overlap, because different probes access different kinds of information, realising powerful synergies. The particular strengths of neutrons include sensitivity to light elements such as hydrogen; the ability to distinguish between different elements; the non-destructiveness of the beam in terms of sample
Figure 1: Non-destructive imaging of an Indonesian dagger sheath, illustrating how neutrons mitigate the obscuring effects of the outer metal cover on images of the inner wooden parts. Top left: A photograph of the dagger and the sheath, which has an outer metal cover (containing silver) and an inner wooden structure. Top right: A neutron transmission (radiography) image. Bottom left and right: 3D renderings of neutron and X-ray tomography data, respectively. Courtesy of E.H. Lehmann [1].

Figure 2: Dirac strings and a Skyrmion lattice. Left: A pair of separated monopoles, in red and blue, with a chain of inverted dipoles between them. Dirac strings are highlighted in white with the associated magnetic field lines [2]. Right: Magnetic vortex spin ordering in a Skyrmion lattice as first revealed by neutron scattering [3].
integrity; the power to probe magnetic structure; and the capability to penetrate many materials, making possible the investigation of samples in environments that would stop other forms of radiation.

The value of a scattering probe also depends on the performance of available sources of radiation. In that respect, investigations using X-rays have experienced dramatic progress through the ongoing development of synchrotron light sources and X-ray free electron lasers. Electron microscopy and nuclear magnetic resonance (NMR) methods also have benefited from significant ongoing advances. Similarly, ESS will offer gain factors of more than an order of magnitude over current neutron sources.

ESS will have a unique ability to study a broad range of structures and time scales due to its long, high-intensity neutron pulses. ESS will offer neutron beams of unparalleled brightness, delivering a peak flux 30 times higher than the world’s most powerful reactor-based neutron source, and five times more power than any accelerator-based spallation source. Its high brightness will provide an unprecedented ability to probe weak signals and systems that change over time, or to measure within a small volume. This last ability is particularly useful for real-world heterogeneous samples or for materials for which only small sample quantities are available. The bright neutron beams will be delivered in a unique time structure, with long neutron pulses (2.86 ms) at low frequency (14 Hz). This structure is very well matched to the requirements of long-wavelength neutrons. To fully exploit the long-pulse structure, ESS will rely on components such as guides and choppers to adapt resolution and dynamic range to each individual experiment, rather than hard-wiring these parameters into the design of the source and instruments as has been done at current spallation and reactor sources. The result will be unmatched instrument flexibility, which will allow the user to zoom in or out of the features of interest while varying the resolution to exactly match the time or spatial correlations under study. The high flux and unique time structure will make possible many investigations that are out of range today, significantly expanding the scientific possibilities.

The spallation source will deliver neutron beams to a suite of research instruments, each devised to extract different kinds of information from the samples studied. The instruments will be adapted to meet the requirements of a wide range of scientific disciplines. The science drivers identified for ESS are soft condensed matter, life science, magnetic and electronic phenomena, chemistry of materials, energy research, engineering materials and geosciences, archaeology and heritage conservation, and fundamental and particle physics. Many of these areas have long traditions using neutron techniques, while in others, the use of neutron techniques is on the rise. It is important that ESS accommodate the science of today while allowing flexibility to meet the developments of tomorrow. The specialised instruments will collectively provide researchers with vital information complementary to information from other methods, such as the X-rays provided by the MAX IV synchrotron that will be ESS’s immediate neighbour. To fully exploit the source performance, ESS’s instruments will employ new technology and novel approaches in their design.

Figure 3 shows the neutron beamline and instrument layout for a reference suite of 22 instruments, selected for illustrative purposes from the 40-odd instrument concepts presently under development. The instruments that actually will be built are likely to be quite different from those in the reference suite, since instrument selection will take place in a staged process, starting in 2013. The design phase for the instruments will continue past 2020, when the final two instrument concepts are slated for selection. This staged approach will permit ESS to remain engaged with the European user community and to choose instrument designs that are state-of-the-art and scientifically relevant when they enter user operation.

In order to make use of the enormous flexibility that the long neutron pulse provides, ESS will use neutron choppers to variably select the sections of the pulse that are needed for a specific instrument. To realise the optimum use of the high flux available, neutron optical components such as focusing guides and polarising mirrors also will be used. In each neutron research instrument, neutrons are detected by a nuclear interaction in a “converter material.” Most flagship instruments at current sources use an isotope of helium, $^3$He, as this converter material. New kinds of neutron detectors are urgently needed, due to the very limited availability of $^3$He. For this reason, the Detector Group was the first neutron technology group established in Lund in July 2010. ESS has established collaborations to develop $^6$B-based detector technology. The collaborations aim both to build up a core of competence in detector development in the Lund region to support ESS’s needs during the construction phase, and to develop capacity in Europe as a whole.

Specialised instruments will not be sufficient by themselves to fully exploit the potential of ESS. Extensive infrastructure also will be required to enable users to make the most productive use of research instruments. This area will be a key strength of ESS. Crucial user infrastructure will include sample preparation, characterisation, and specialised synthesis laboratories; detector and sample environment systems; and information technology and computational support. ESS users will benefit from the Data Management
Figure 3: Neutron beamline and instrument layout for the reference instrument suite, which is presented for illustrative purposes. The instruments that actually will be built will be chosen in an ongoing process in which several instrument concepts are selected every year, starting in 2013 and ending in 2020. Labels for the nine numbered instruments in the upper left of the figure are listed below the image.

and Software Centre (DMSC) that will be located at the Nørre Campus of the University of Copenhagen across the Øresund from the experimental stations in Lund. The computational and software solutions being developed at DMSC will provide users with a coherent experience, providing user-centred software for instrument control, efficient data reduction, real-time data visualisation, intuitive data analysis and computational support for modelling and simulations. This comprehensive set of computational solutions will add value to the neutron data collected, and will establish a new standard for neutron facilities. It also will make neutron techniques more accessible to researchers from fields that do not have long histories using these tools, but for which neutrons hold significant promise of yielding new insights.

An ongoing series of ESS science symposia and workshops promotes communication between ESS and the scientific community, ensuring that the instrument suite, supporting infrastructure and computational options will be able to respond to the diverse needs of researchers from a broad range of disciplines as they evolve over time.

The target station

The main function of the target station is to convert the high-energy proton beam from the accelerator into low-energy neutron beams with the greatest possible efficiency. Three groups of target station subsystems deliver this key functionality. The first group consists of the target monolith and the components it houses, including the target wheel. The second group is made up of fluid systems, including the closed cooling circuits and the radioactive gaseous effluents and confinement (RGEC) system. The third group
Figure 4: Target station functionalities.

includes the handling and logistics subsystems for the radioactive components from the target station operation. This group includes active cells, casks and remote handling systems. These subsystems transport, exchange, maintain, process, package, store and release the used radioactive components from the target station operation. Figure 4 provides an overview of the target station functionalities.

Target station interfaces with the rest of the ESS project are complex. Target station design has been coordinated with accelerator design and with the requirements of the neutron scattering instruments. The target station safety system also has a number of protected interfaces with the facility-wide integrated control system, and the target station design has a large impact on target building and conventional facilities design, and vice versa. For robust and cost-effective design of the target station components, ESS has used advanced multi-physics simulation techniques in an iterative fashion, both for optimising neutron beam performance and for addressing issues of technical realisation and operation. This approach begins with calculation of the beam profile using beam dynamics calculation tools. A particle transport code is then applied to calculate volumetric heat depositions in irradiated target station components. Finally, the calculated local volumetric heat deposition configurations are used in advanced coupled flow, thermal and mechanical simulations to estimate the thermal and mechanical loads on the system. A database of the characteristics of the irradiated and un-irradiated materials used in the target system has been constructed using information from experiments, design codes and the scholarly literature. This database provides a crucial underpinning for the engineering design of target system components.

The monolith, target and associated subsystems will interact directly with protons and/or neutrons. This group of target subsystems includes the proton beam window, the rotating target wheel system, the moderator-reflector assembly and the beam extraction system. The self-contained target safety system, which overarches the whole target station and provides for facility safety at the highest level, is also a crucial part of this group. The target material (tungsten) will transform high-energy protons to fast neutrons. The moderator-reflector system surrounding the target will transform the fast neutrons into slow neutrons. These neutronically-activated subsystems will be housed in the target monolith, which will be composed of 7000 tons of steel shielding. The target monolith has been designed to contain the highly-penetrating gamma and fast neutron radiation that will be created by the spallation and radioactive decay processes. The baseline technology chosen for the ESS target design is a rotating tungsten target cooled by inert helium gas. The target surface area will be large enough so that in the event of a loss of power, passive
conduction, convection and radiative cooling would prevent the afterheat of radioactive decay from leading to unsafe temperatures with a significant safety margin.

In order to provide a complete and robust technical underpinning for the ESS design, two other target concepts have been explored in addition to the baseline design. A water-cooled rotating tungsten target has been designated as the back-up option. A lead-bismuth-eutectic (LBE) target, using liquid metal both as target material and coolant, was studied as a comparative option particularly with respect to environmental considerations. The results of this comparative study proved favourable to the baseline option.

The accelerator

ESS is an accelerator-driven neutron spallation source. The linear accelerator, or linac, is thus a critical component. The role of the accelerator is straightforward. It creates protons at the ion source, accelerates them to an appropriate energy, and steers them onto the target to create neutrons via the spallation process for use by a suite of research instruments. The general lay-out of the ESS linac is shown in Figure 5.

The proton ion source is a compact electron cyclotron resonance source (ECR) similar to those currently in operation in Catania, Sicily and at CEA-Saclay outside Paris. The beam from the ion source is transported through a low energy beam transport (LEBT) section to the radio-frequency quadrupole (RFQ) for bunching and acceleration. A similar RFQ presently under commissioning at CEA-Saclay, will be tested with realistic ESS performance parameters. The beam is transported from the RFQ and matched to the normal conducting drift tube linac (DTL) through a medium energy beam transport (MEBT) section. Leaving the DTL, the beam enters the superconducting portion of the linac, where acceleration is accomplished via superconducting radio frequency (SRF) cavities constructed from niobium. The low temperatures required for superconduction are achieved by immersing the cavities in liquid helium at a nominal temperature of 2 K. An individual helium tank surrounds each cavity. From the superconducting portion of the linac, the beam is transported via the high energy beam transport (HEBT) section to the target.

The energy that accelerates the proton beam is provided by the radio frequency (RF) system that converts the AC power from the electrical grid to the appropriate RF frequencies required to drive the various accelerator components. This system includes the RF sources and conditioners (klystrons and modulators), the RF distribution system and the RF controls. The high level requirement of 95% reliability (availability) strongly influences the baseline design choices. High reliability requires that the accelerator must run, after re-tuning, even if multiple RF source-cavity stations are inoperable. It also requires a segmented cryomodule design, in which each cryomodule may be cooled down or warmed up independently of the others. Figure 6 shows a view of the tunnel including cryomodules.

The beam physics design of the linac has reached a high level of maturity. Inputs to the design include ESS’s high-level parameters; mechanical properties such as the length of all linac components; constraints such as the maximum cavity gradients and the rating of the power couplers; optimisation criteria such as a desire for a minimum linac length and for small numbers of cavities and cryomodules; the need for high beam quality and small losses; and external factors such as the development of production capabilities and collaborations. The resulting configuration is a robust lattice with very small emittance growth, in which design margins and tolerances to faults and parameter variations are balanced with effectiveness in terms of cost and schedule. The linac configuration must be tolerant against static and dynamic variations.

Figure 5: Block diagram of the ESS accelerator. Orange items (such as the radio frequency quadrupole and the drift tube linac) are normal conducting, while blue items (the spoke resonators and the medium- and high-β elliptical cavities) are superconducting.
in parameter values, and beam losses must stay small within the range of expected variations. Also, the machine should, as far as possible, be able to run even if some components fail. To address these issues, a comprehensive study of alignment and field errors has been initiated, and investigations of the effects of faults and failures have begun. Figure 7 shows simulations of the maximum radius of the proton beam at different points along the linac for an ideal machine and for machines with various amplitudes of errors.

Successful operation of the accelerator requires detailed knowledge of the condition and location of the proton beam. The accelerator will be equipped with an array of beam instrumentation for this purpose. Beam loss monitoring (BLM) is arguably the most important diagnostic system of the linac. It will serve the dual purpose of keeping the machine safe from beam-induced damage and avoiding excessive machine activation by providing critical input to the machine protection system. Thus, the system will be designed so as not to have any blind spots. As the BLM system will be a major tool for beam tune-up, it also will be designed in a way that enables it to pinpoint the loss location as precisely as possible.

Figure 7: Robust design requires that the linac function even in the presence of alignment and field errors. The plot shows results from the simulation of maximum beam radius for an ideal machine (black curve) and for machines with various amplitudes of deviation from that ideal (coloured curves).
The integrated control system

The integrated control system (ICS) is responsible for the whole ESS machine and facility: Accelerator, target, neutron scattering instruments and conventional facilities. This unified approach keeps the costs of development, maintenance and support relatively low. ESS has selected a standardised, field-proven controls framework, the Experimental Physics and Industrial Control System (EPICS), which was originally developed jointly by Argonne and Los Alamos National Laboratories in the United States of America. Complementing this selection are best practices and experience from similar facilities regarding platform standardisation, control system development and device integration and commissioning. The components of ICS include the control system core, the control boxes, the database management system, and the human machine interface.

The control system core is a set of systems and tools that make it possible for the control system to provide required data, information and services to engineers, operators, physicists and the facility itself. The core components are the timing system that makes possible clock synchronisation across the facility, the machine protection system (MPS) that helps avoid damage to the machine’s equipment due to beam losses, the personnel protection system (PPS) that prevents harm due to radiological risks, and a set of control system services that help with maintenance and operations.

Control boxes are servers that control a collection of equipment (for example a radio frequency cavity). ICS will include many control boxes, each of which can be assigned to one supplier, such as an internal team, a collaborating institute or a commercial vendor. This approach facilitates a clear division of responsibilities and makes integration much easier. A control box is composed of a standardised hardware platform, components, development tools and services. On the top level, it interfaces with the core control system components (timing, MPS, PPS) and with the human-machine interface. At the bottom, it interfaces with the equipment and parts of the facility through a set of analogue and digital signals, real-time control loops and other communication buses.

The central data management system is named BLED (beam line element databases). BLED is a set of databases, tools and services that is used to store, manage and access data. It holds vital control system configuration and physics-related (lattice) information about the accelerator, target and instruments. It facilitates control system configuration by bringing together direct input-output controller configuration and real-time data from proton and neutron beam line models. BLED also simplifies development and speeds up the code-test-debug cycle. The set of tools that access BLED will be tailored to the needs of different categories of users, such as staff physicists, engineers, and operators; external partner laboratories; and visiting experimental instrument users.

The human-machine interface will be vital to providing a high-quality user experience. It encompasses a wide array of devices and software tools, from control room screens to engineering terminal windows; from beam physics data tools to post-mortem data analysis tools. It will serve users with a wide range of computer skills from widely varied backgrounds. ESS is developing a set of user profiles to accommodate this diverse range of use-cases and users.

Specialised technical services

ESS requires three specialised technical systems: The cryogenic system, the vacuum system and the test stands. These systems support all three areas of the ESS: Accelerator, target and experiments. The system designs are conservative and based on experience at other facilities such as CERN in Geneva, Switzerland; SNS in Oak Ridge, Tennessee; and CEA-Saclay.

The cryogenic system consists of the linac cryoplant that provides cooling for cryomodules; the test and instruments cryoplant that provides cooling for test stands and liquid helium for instruments; the target cryoplant that provides 16 K helium cooling for the target station’s hydrogen moderators; and the distribution system that connects the linac cryoplant to cryomodules. The linac cryoplant and test/instrument cryoplant share common gas management and storage systems. The target cryoplant system is completely separate due to the potential for tritium contamination. The cryogenic systems have been designed to meet sustainability goals through measures such as helium conservation and heat recovery. The cryogenic system also has been designed with an adequate margin of error to assure that its capacity will be large enough to meet ESS’s needs.

The vacuum system provides vacuum for the linac beam line, target system and instrument lines. It
uses well-established technology and procedures based on experience at similar facilities, including SNS in the United States, and J-PARC in Japan. It poses low technical risk.

Test stands provide testing and validation of both RF equipment (klystrons and modulators) and cryomodules. Cryogenic connection to cryomodules in the test stands will prototype similar connections in the linac tunnel. The test stand programme is robust against uncertainty in the ESS construction schedule by allowing for RF equipment testing in a temporary location if necessary. All cryomodules will be tested at nominal temperatures and RF power levels before tunnel installation. Cryomodule testing will take place at test stands in Lund and Uppsala.

Conventional facilities

The term “conventional facilities” refers to the spaces required to house ESS research equipment, machines and instruments and to accommodate the human beings who will either make use of the facility directly, or who will support its operation and maintenance. The overarching goal of the Conventional Facilities (CF) project is to deliver the physical space for a sustainable research facility in an environmentally friendly way. This includes meeting energy-related objectives and requirements; creating a good, safe and accessible working environment; creating an outdoor environment that promotes biodiversity and sustainable transportation; and using environmentally sound materials. During construction, CF will adopt a life-cycle perspective on the ESS facility, fulfilling requirements imposed as part of the Swedish environmental and construction permitting process and delivering the project within schedule and within budget. CF is also responsible for the mechanical and electrical services necessary for the proper functioning of the facility. Figure 8 locates the ESS site on maps of the region, while Figure 9 provides a preliminary sketch of the layout of the main components of the facility.

ESS will locate its facility on a 74.2 hectare site situated northeast of the town of Lund in the region of Skåne in southern Sweden. The site is located between Odarslösvägen and the E22 highway, shaded in blue in the right hand panel of Figure 8. CF has studied the location and conditions at the site in terms of geography, current infrastructure, archaeology, and scientific and industrial environment. CF has also carried out extensive studies of ground conditions at the site, and evaluated alternative approaches to providing the facility’s foundations in light of those ground conditions. The site, on the outskirts of the Brunnsäng district of the city of Lund, is located in a highly developed scientific and industrial environment, providing access to an educated and technically skilled workforce, and proximity to Lund University and several major research centres. In addition, Lund and the surrounding region are home to
a thriving knowledge-based industrial sector, including such major international companies as Ericsson, Tetra Pak and Alfa Laval. ESS’s immediate neighbours will include the MAX IV synchrotron and Lund Science Village. Brunnshög is undergoing extensive growth and development. Regional land use plans call for a mixed-use neighbourhood with about 3000 dwellings, and with businesses providing employment for 20,000 to 25,000 individuals by 2025. Regional authorities will construct a tramway from Lund Central Station to the area. In addition, local buses and bicycle routes will be available.

The facility stretches over a considerable area. It is the responsibility of CF to create an efficient and functional logistics network and to provide a transportation system that will facilitate communication, social interaction, and the gradual addition of further buildings and instrument halls. Notable logistical challenges include the design of facilities and procedures to handle the complex and delicate sample materials that will be investigated by the ESS instruments, and the provision of remote handling and other systems required to deal with activated materials. CF is also responsible for planning and constructing the earthworks needed to create roads, parking spaces and landscaping, including the detention ponds required to treat storm water. The specific requirements of the storm water system that will protect external recipients from pollution from the facility receive particular attention. Buildings must reflect ESS’s core values of excellence, openness and sustainability. The main buildings include the accelerator buildings,
The scientific and symbolic value of the facility calls for a work of architectural and functional excellence. The summer of 2012 saw the launch of the ESS architectural design competition, undertaken under European Union rules and regulations. Experts in architecture, landscaping, economy and user aspects were invited to advise the jury. On 19 February, 2013, a team headed by Henning Larsen Architects was selected. The winning proposal provides a clear concept for the overall design of the site. The centrepiece target building is instantly recognisable by its overhanging, oval roof. The roof provides an ordering principle for the various buildings around the target area. In front of the target building, a dense campus area is planned, as shown in Figure 10.

Integration

The ESS integration strategy facilitates the success of the programme by progressively combining system elements in accordance with design requirements. It sets out procedures to ensure that interim assembly configurations are tested repeatedly, in order to assure the necessary flow of information and data across interfaces, to reduce interference risk and to minimise errors. ESS is implementing a quality management system based on the principles of ISO-9001. Systems engineering will ensure the efficient management of non-conformities and change requests. ESS’s building information modelling system defines a uniform way of operating in civil engineering work and facility construction. The internal manual, Standards, Norms and Guidelines Recommended for the Design and Construction of ESS, constitutes a platform of standards recognised to be valid and applicable. The Standards Working Group is responsible for keeping the platform current with evolving norms and standards adopted by relevant national and international agencies and
professional groups. Design integration focuses on the interconnections between system components. The plant breakdown structure allows easy interface identification and provides a framework for the coherent organisation of documents and CAD assembly structures. Configuration management is achieved through configuration identification, interface and document management and change control. The plant layout is the three-dimensional model virtualisation of the facility. It is robustly linked to the proton and neutron beam lattices by BLED, the centralised system of databases and tools and services that is used to store, manage and access data.

Survey and alignment helps to accomplish the required positioning accuracy of the ESS components. A surface monument network will be connected to the accelerator axis, the target ports and the neutron lines in order to establish a relation between the global position coordinates and the components. ESS will maintain a centralised, freely accessible database of standardised components that will guide personnel in Lund and at partner laboratories during the selection of devices for their applications. Benefits from component standardisation include economies of scale, reduced burden on procurement offices, ease of maintenance and supply, and more efficient management of inventory. Product life-cycle management (PLM) encompasses the tools and procedures developed to ensure component traceability from design through installation, operation and decommissioning. Integration activities include a variety of quality-related tasks, such as acceptance testing and component alignment. The first major challenge for integration activities is to successfully bring the facility through the installation process. The final goal is to achieve system assembly and interconnection.

**Commissioning**

For a complex facility such as ESS, the transition from construction to operation has to be planned early in the construction phase so that it can be made in an organised and effective manner. The transition from construction to operations will stretch from 2017, when the first building is completed and taken into operation, to 2025 when the last of the 22 instruments is completed and 5 MW of power is reached. Building on experience from other research facilities, ESS has developed a commissioning strategy and methodology. A main element of this strategy is an initial proton beam commissioning with a staged approach and early start. This will be followed by an aggressive early increase in beam power, in order to identify any machine limitations as soon as possible, before a large number of users are expecting reliable beam. Naturally, the commissioning and power ramp-up will comply with the limits set by the licenses and permits ESS has been granted by the relevant legal authorities. Systems will be commissioned first without beam, and later with beam.

The conventional facilities commissioning includes bringing all the conventional parts and systems of the facility into an operational state such that they perform all intended functions and meet design and operational criteria. Buildings and systems will be completed and commissioned in a timely fashion in order to allow efficient and early installation and commissioning of machine and instruments systems. The accelerator will be commissioned in stages: The front-end and ion source will be commissioned first, followed by the drift tube linac, the superconducting linac with spoke resonators, all medium-$\beta$ and high-$\beta$ elliptical cavities, and finally the high energy beam transport and the transfer to the target. For commissioning of the first stages, a movable beam dump and a provisional control system will be used to allow parallel installation of the later stages. The target station will be the last major machine component to be commissioned. It includes the neutron production systems (target, moderators and pre-moderators, reflectors, proton beam window), the ancillary systems and the safety systems (shielding, confinement barriers). Activation levels will be kept low during the initial stages of commissioning in order to allow hands-on work. The neutron instruments will be commissioned individually as the construction of each instrument is completed. The instruments will first be commissioned without beam, followed by a commissioning with beam, and later, a period of scientific commissioning during which the instrument will be brought into scientific operation suitable for external users.

**Emission control**

ESS has prioritised developing a waste management strategy for irradiated materials that addresses regulatory requirements, radiological characterisation, waste treatment and conditioning, waste disposal, de-
commissioning, and environmental concerns. ESS is very serious about planning for the safe operation of the facility, and for its safe decommissioning at the end of its operating life.

The handling and conditioning of radioactive waste requires complex engineering solutions that are strictly regulated under Swedish law. As the pre-construction and design phase of ESS’s life-cycle nears its end, ESS has already made substantial progress in estimating levels of radioactive waste and emissions, and in developing protocols for managing waste. A series of technical reports detailing quantitative results and concrete plans demonstrates the commitment and organisational and intellectual capacity of ESS to meet the demands of Swedish law and regulation and to comply with Swedish waste management policy. Collectively, these analyses make it clear that ESS will be a good neighbour, and will not damage the health of the community or the environment. Within the Swedish system, the generator of radioactive waste must provide information about the radionuclide inventory before the removal of the waste into final repositories is permitted. ESS will rely on three complementary methods for waste characterisation. These methods are Monte Carlo calculations, the matrix method, and on-site radiation detection and measurement.

ESS has developed a waste management logistical plan that divides ESS waste streams into categories according to a risk-based assessment, and proposes a treatment protocol optimised for each specific material’s characteristics. Treatment, shipping and disposal of ESS waste are feasible within the Swedish system. ESS has also made preliminary estimates of the radioactive waste and emissions generated in fluid systems. The outcomes of these studies provide data for the environmental impact analysis of normal ESS operation. In addition, ESS has conducted a parametric study of the performance of the purification system within the helium cooling circuit. This work confirmed that safe management of radionuclides is readily achievable. As required for environmental impact analyses under Swedish law, the annual dose to a reference person from exposure due to routine release of radionuclides was estimated. Calculations indicated that dominant contributions come from linac emissions through the stack, while the contribution from dismantling the target every five years is almost negligible. Under the study’s assumptions, doses are less than the ESS limit of 10 µSv/year for a single pathway. Rough modelling of activity transport within groundwater under very conservative assumptions indicated a negligible contribution to the total annual dose to the public. The radiological consequences of potential accidental releases were also estimated. Contaminants that could be released during the most severe hypothetical design basis accident (DBA) were ranked by their importance with respect to dose. For the very conservative value of 0.5% volatile release fraction, the total estimated dose to individuals in the immediate vicinity of the facility was around 6 mSv.

When the facility enters the final phase of its life-cycle, decommissioning will take place over a period of five years. ESS has chosen immediate dismantling as its decommissioning reference strategy. Several factors favour this approach over phased decommissioning, perhaps the most important of which is being able to draw on the accumulated experience of ESS’s operating staff during decommissioning. ESS will return the site to green field status, permitting unrestricted future use.

Safety and security

ESS prioritises prevention of harm to employees, the public, and the environment from both radiation and conventional safety threats. In 2011, ESS formally adopted the following project-wide set of General Safety Objectives:

- “To protect individuals, society and the environment from harm arising from the construction, operation and decommissioning of the ESS facility.
- To ensure that in normal operation, exposure of personnel to hazards within the facility is controlled, kept within prescribed limits, and minimised.
- To prevent accidents with high confidence.
- To ensure that any abnormal operational event has minimal consequences for ESS personnel and for the public.
- To minimise the hazardous waste arising from the operation and decommissioning of ESS, both in its quantity and level of hazard potential.”
These overarching goals will guide ESS through all phases of its multi-decade life-cycle. They apply to all aspects of safety at the facility, including radiation, fire, cryogenics, chemicals, heavy loads and other hazardous items or situations. The security systems of the facility will be designed to meet basic in-house security needs such as deterrence of theft and vandalism and to comply with regulatory requirements, while also taking into account the need for users and personnel to work in an open and friendly atmosphere.

While ESS is classified as a non-nuclear facility from the standpoint of Swedish law, it will produce activated materials. In developing its safety programmes, ESS has profited from decades of collaboration and exchange among regulators and facility operators within the nuclear community about how to handle such materials. This accumulated collective knowledge base informs ESS’s own safety objectives and programme. The ESS licensing process is governed by three Swedish laws: the Radiation Protection Act, the Environmental Code and the Planning and Building Act. On 15 March 2012, ESS submitted a formal application for a permit to begin construction to the Swedish Radiation Safety Authority (SSM). On the same day, ESS also sent in its application to the Swedish Environmental Court.

In accordance with well-established international best practices, a few basic principles constitute the framework for the ESS safety programme: Exposure to hazards will be as low as reasonably achievable (ALARA); multiple and redundant levels of safety barriers and protective systems will provide defence-in-depth; ESS design will incorporate both passive and active safety measures; and an ongoing process of review and assessment of safety systems will shape the entire engineering design process. These principles will enforce the safety culture within the ESS organisation. Maintaining that safety culture will be a top priority for ESS management. In accordance with the ALARA principle, ESS guidelines call for more restrictive dose limits than does Swedish law. ESS will apply the defence-in-depth concept in order to minimise deviations from normal operation, to prevent accidents, and to mitigate the consequences of abnormal events. ESS will use a set of physical confinement barriers that operate independently of one another to prevent and mitigate potential releases of radioactive isotopes. Three confinement barriers will contain the nuclide inventory in the target, caused by proton bombardment. All possible other nuclide inventories at ESS will have at least two safety barriers.

Passive safety systems rely on facility features whose very nature acts to prevent accidents or to limit the adverse consequences of accidents independently of human intervention. The ESS design incorporates two important passive safety systems. First, the linac will depend on the continuous input of power from the electrical grid to produce beam. This is a powerful safety feature, because if the external power supply is interrupted for any reason, the accelerator will automatically shut itself down. Unlike nuclear reactors, there is no danger of ESS “going critical” once it has been accidentally or deliberately cut off from the power grid. The second important feature of the ESS design from the safety perspective involves the ESS target station cooling system. The most likely reason for a loss of cooling system function is an electric power interruption. Although this guarantees an instantaneous shut-down of the accelerator, heat production in the target will continue for some time. ESS’s rotating, helium-gas-cooled tungsten target, with its 2.5 m diameter, offers a large enough surface area for passive cooling to avoid dangerous temperatures with a significant safety margin, eliminating the risk of target overheating, even in the absence of an active cooling system.

ESS’s active safety systems will include mechanical, electrical, and instrumentation and control components. They will ensure that the facility operates safely, and that safety is maintained in the event of an incident. Active safety systems also encompass ESS protocols governing installations and training programs to ensure that all employees act in accordance with prevailing instructions and in compliance with Swedish regulation. ESS protocols will lay out a fixed schedule for maintenance, testing and adjustment of many mechanical and electrical safety devices, and for radiation monitoring of the experimental instruments.

**Conclusion**

After more than 20 years of work we find ourselves at the point where the construction of ESS will begin. This comes about thanks to the dedication of countless hundreds, and perhaps thousands, of people who have contributed to bringing the project to where it is today. The publication in 2013 of the *Technical Design Report* demonstrates the fruits of that work – the scientific drive, the technological inventiveness, the administrative determination. We could not have reached this point without the support of our funding bodies and, ultimately, of the taxpayers who support the funding bodies. We are well aware of
the responsibility we carry. We will deliver.

The TDR comes one year after the *Conceptual Design Report* (CDR) was published. It is not simply one year advanced from the CDR, but rather contains the work, the studies and the designs contributed by perhaps four times as many people as contributed to the CDR. There has been a multiplicative process in play. Equally well, whilst the CDR was more or less a stand-alone document, the TDR is but one of the whole sheaf of documents of more than one thousand pages that together represent the current state of knowledge. They in turn stand on the foundation studies and technical reports that have been produced over the last few years in Lund, in the laboratories of our partner countries and indeed around the world.

This body of knowledge has reached a certain state of maturity. It is, thanks to the nature of a scientific facility, incomplete. It will always be incomplete. However it represents what is both necessary and sufficient to allow a clear decision from funding bodies around Europe to officially start the construction phase of ESS.

As Ivan Turgenev said:

*If we wait for the moment when everything, absolutely everything is ready, we shall never begin.*

It is time to begin!
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