Chapter 9

Commissioning

Chapter abstract

Summary: For a complex facility such as ESS, the transition from construction to operation has to be planned well ahead and early in the construction phase so that it can be made in an organised and effective manner. Experience from other research facilities shows that managing the interface between systems during start-up requires planning and structured procedures in order to keep to schedule and manage risks for personnel and equipment. This chapter describes the technical aspects of this transition for all major parts of the facility: the conventional facilities including technical infrastructure, the accelerator, the target, the instruments and the integrated control systems. The chapter presents a schedule for the transition stretching from when the first building is completed and taken into operation in 2016 to when the last of the 22 instruments is completed in 2025 and 5 MW of power is reached.

Strategy and methodology. 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 and high beta elliptical cavities; and finally the high energy beam transport (HEBT) 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, 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 where the instrument is brought into scientific operation suitable for external users.

9.1 Introduction

Experience from other research facilities show that the transition from construction to operations for a complex facility such as ESS requires a significant a planning effort already at an early stage in order to efficiently reach operational requirements, keep to schedule and manage risks for personnel and equipment. The purpose of this chapter is to describe the technical aspects of how ESS will make the transition from the construction phase into the operations phase on a high level, that is how the main technical systems of ESS will be commissioned together. The management, organisation and approval procedures for this transition are described in the Transition to Operations document [605].

The scope of this chapter includes all parts of the facility: the conventional facilities including technical infrastructure, the accelerator, the target and the instruments. In terms of programme schedule, it stretches from when the first building is completed and taken into operation in 2016 to when the last of the 22 instruments is completed in 2025 and 5 MW of power is reached. Notably, it includes the commissioning of the machine, the production of the first neutrons, the power ramp-up and the commissioning of the instruments. More precisely, the commissioning of any system at ESS starts with the completion of the installation and ends with routine operation at full specification. This chapter describes the key activities and technical aspects related to the commissioning of the main systems of the facility. The activities and schedules presented in this chapter follow the project specifications for the construction and operation of the accelerator, the target, instruments and conventional facilities [42, 606–609]. It is important to note that it is not a project specification in itself.

This chapter describes the strategy and methodology to be applied, the commissioning of the conventional facilities, the accelerator, the target station and the instruments and clarifies a few key definitions. It builds on lessons learnt from other facilities, in particular from the commissioning of the SNS and the MEGAPIE target experiment. A few key lessons are listed in Section 9.8. In the chapter, the commissioning of the control systems, the data management systems and machine- and personnel protection systems are described together with aforementioned main parts of the facility but it also has a section of its own. The requirements and limits set by licensing and regulatory requirements are described throughout the document.

Definitions

1. **Beam commissioning:** initial transport of beam through a beam line, following equipment installation during the construction phase.

2. **Cold commissioning:** Start up of systems without producing a proton beam. Approximately no ionising radiation or radioactive materials is generated.

3. **Hot commissioning:** Start up of systems including producing a proton beam. Ionising radiation and radioactive materials can be generated.

4. **Power ramp-up:** Increase in the operational power on target in the period 2019 to 2025 to 5 MW.

5. **Machine reliability:** Machine reliability: the fraction of the time scheduled for neutron production that high power beam is delivered on target [42].

6. **Machine availability:** the fraction of the time (over a year) that the machine is available for neutron production with a high power beam being delivered to the target [42].

9.2 Strategy and methodology

The overall strategy for the initial commissioning of beam through the accelerator, and for the subsequent increase in machine performance to its design levels is described here. Initial beam commissioning culminates with the delivery of beam on the target and production of first neutrons in 2019. A primary aspect of the initial beam commissioning is a staged approach with an early start. The period following the initial beam commissioning through 2025 involves increasing the beam power, operational hours, machine reliability and the deployment of the scientific instruments to meet ESS goals. In this power ramp-up period, an aggressive early increase in beam power is planned, to identify any machine limitations as soon as possible, before a large number of users are expecting reliable beam.

The commissioning and power ramp up must be conducted within the limits set by the licenses and permits given. The Environmental Court will set conditions for the construction and operation of the facility for all matters not concerning radiation. The Radiation Safety Authority will set conditions for all matters concerning radiation and radioactive materials. According to the plan agreed with the authority, a license will be granted for ESS construction, another for test operation (commissioning) and later full operations at full power. Accordingly, permits and licenses will set conditions for commissioning both with and without beam. Reporting to relevant authorities during commissioning will continue, just as did reporting to the same authorities during construction. An open dialogue, monitoring and inspections are foreseen and it is expected that the licensing authorities will follow the commissioning of the facility closely.

Further, every care will be taken not to damage the machine or expose personnel to undue risks. This may in fact impose more restrictive limits than the licenses. The machine protection system (MPS) and the personnel protection system (PPS) must therefore be commissioned early and reach a level of functionality that can properly protect machine and personnel during commissioning. The ESS accelerator will be the worlds most powerful proton accelerator and many of its systems represent state of the art technologies. As ESS is a green-field site, none of the systems will have a history of institutional support at the central site. Having all these systems work together in concert will be challenging, and beam commissioning is the first time all the supporting systems truly need to work in an integrated fashion. Discovering the inevitable issues that will surface during beam commissioning as soon as possible will give system developers an early opportunity to modify their systems. In fact, the commissioning of sections of the accelerator will be a valuable integration exercise. As such, a staged approach to beam commissioning is planned in order to facilitate early system adjustments.

The staged commissioning provides several opportunities to run systems together, as opposed to installing all the ESS accelerator systems before attempting to run beam. Four commissioning stages are envisioned for the period 2016 through 2019. Lessons learnt in the early commissioning will facilitate commissioning in later periods, when more is at stake, and will also facilitate the initial power ramp-up. As an example of this approach, the SNS beam-commissioning period is shown schematically in Figure 9.1, indicating seven commissioning stages over about 3.5 years [610]. The initial commissioning stages involved accelerator beam-lines of only a few meters. The latter commissioning periods covered much more involved tasks, such as the entire superconducting linac and the entire ring and transport line systems. However less time was needed for these latter tasks, in large part due to the lessons learnt from earlier commissioning experiences. Providing early commissioning stages will be beneficial in the long run, but will require special arrangements initially. The early beam commissioning will require early building occupancy and utility support and the use of a temporary control room setup, and it will coincide with other construction activities on site. Beam commissioning during the construction period need not preclude construction and installation activities in downstream parts of the accelerator, in the target and instrument areas. Installing a temporary shield wall beyond the commissioning beam stop can permit installation activities to proceed downstream in the same tunnel. This was the case for the early commissioning activities at SNS shown in Figure 9.1.

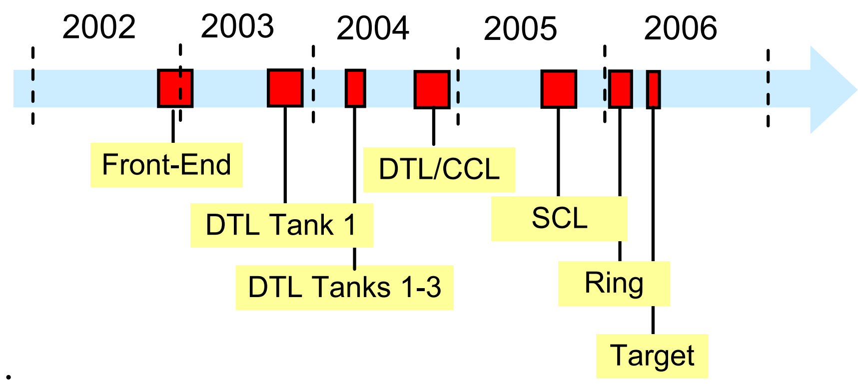

Figure 9.1: Beam commissioning during the SNS construction period, with the commissioning durations indicated in red. Courtesy of SNS.

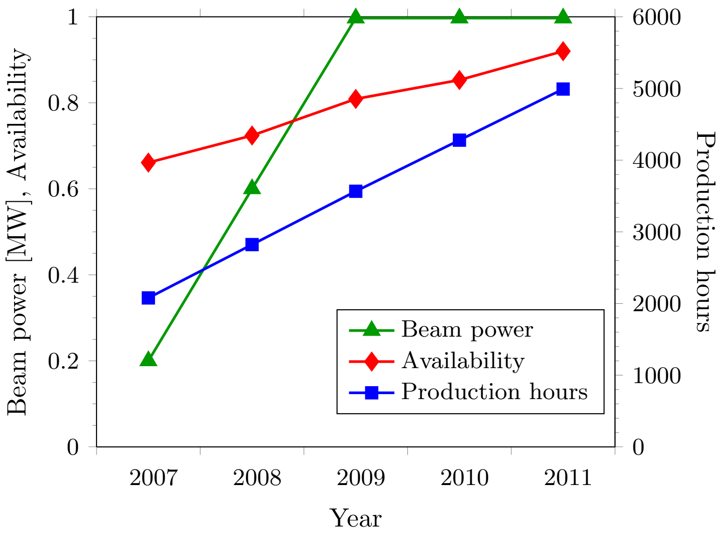

Figure 9.2: Operational metrics for the first 5 years of SNS operations following the initial proton beam on target. The beam power is the maximum beam power delivered during each fiscal year. Courtesy of SNS.

Following the initial delivery of a proton beam to the neutron target in 2019, including the commissioning of the initial set of instruments, a transition to a fully operational facility is planned. In this power ramp-up period, the operational power on target, the operational hours per year, the machine reliability and the number of operational instruments will approach the final facility performance levels, capable of delivering the scientific productivity expected from ESS. Throughout this period there will be a transitional emphasis from accelerator and target development towards an emphasis on supporting the neutron science.

As ESS represents unprecedented accelerator power levels and aims for world-class accelerator reliability, some years will be required to reach full capabilities. Low machine reliability in the initial years during power ramp-up is expected for a new world-class, first-of-a-kind facility. As 2025 approaches, with a large suite of instruments deployed, the disruptions caused by extended machine downtimes will have more severe consequences, and there will be a larger resistance to any change in the accelerator operation that may risk reliability. As such, an aggressive early push on the proton beam power ramp-up is planned, which will help identify any machine weaknesses and allow for appropriate modifications before a large neutron user community is in place at ESS.

This strategy is similar to that employed at SNS. The SNS original transition to operations plan called for a rapid increase in beam power to 1.4 MW over three years, accompanied by slower increases in beam reliability, neutron production hours and reliability [611]. Some actual SNS operational metrics over the first five years following initial delivery of proton beam on target are shown in Figure 9.2. There was an aggressive initial increase in the beam power over the first three years of operation. With the aggressive push for extended high power accelerator operation during the SNS power ramp-up, equipment shortcomings were identified early and efforts initiated for remediation. The identification of equipment issues requiring upgrades in the initial years at SNS is reflected in the low initial level of machine reliability. However, remedial actions taken during 2007-2009 led to reliability increases later on [612]. After 2009, the supported neutron user base had significantly increased, and there was a growing resistance to risking further beam power increases, which could adversely impact reliability [613].

After a neutron scattering instrument construction project is complete, it will enter a hot commissioning phase, using the spallation neutrons to characterise the performance of the instrument. As part of the instruments commissioning readiness review, the instrument team will have prepared a comprehensive commissioning plan. At full power and 95% reliability, instrument commissioning will take at least six months and could take up to two years. For instruments entering the commissioning phase in the initial years of ESSs operations, these plans will take into account the fact that beam operations will be at low power and low reliability. The scientific partners associated with the instrument will be working with the

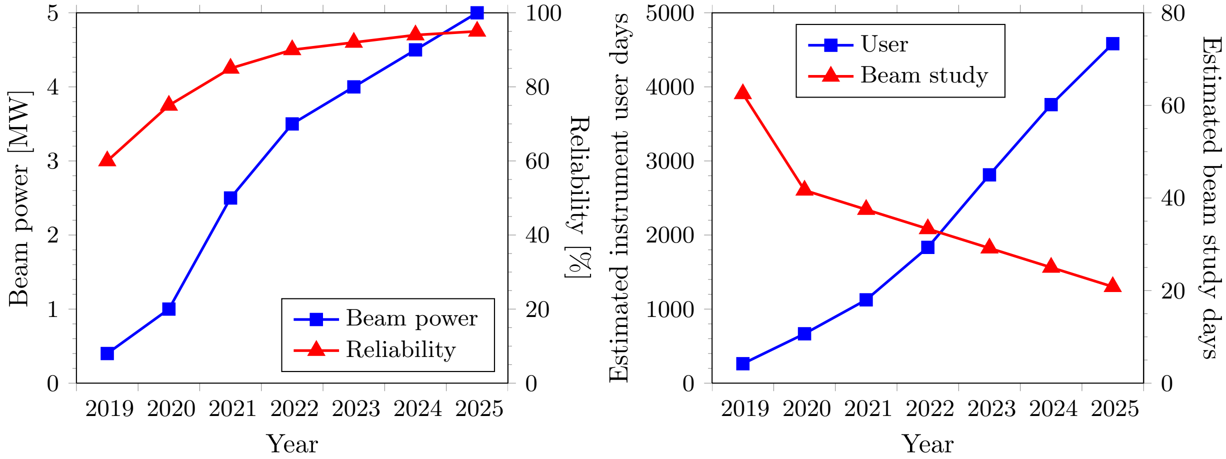

Figure 9.3: High-level goals during the transition period to full operations. Left: The accelerator parameters, indicating a rapid initial increase in power and reliability. Right: Estimates of delivered number of instrument user days and number of days of beam study, approaching the design expectation at the end of 2025.

instrument staff on the commissioning and subsequent early operations of the instruments. These partners will be fully cognisant of the operational status and risks associated with experiments at a facility still building up its experience and capabilities.

Taking into consideration the issues described above, a schedule for delivery of the high level ESS performance goals by the end of 2025 is shown in Figure 9.3. The accelerator parameters shown in Figure 9.3 (left) indicate an aggressive push early on, reaching 90% of full power within 3 years. Machine reliability is expected to be quite low initially, as equipment issues are addressed. Approaching 95% reliability at the end of the transition period will be one of the primary challenges. Figure 9.3 (right) indicates the build-up of operational support for neutron science. Figure 9.4 presents the high level schedule for the main activities and milestones for the transition to operations phase. In reality the beam availability will be low and reliability poor in the initial stage of the commissioning with beam and during the power ramp up. However, a preliminary operations schedule has been produced for planning purposes [614] for the first year in the operations phase. This schedule is shown in Figure 9.5.

9.3 Conventional facilities

For conventional facilities, commissioning means bringing all the conventional parts and systems of the facility, which are completed mechanically and electrically, into an operational state such that they perform all intended functions and meet design criteria. Commissioning tests will verify that the works have been carried out in conformance with technical specifications and relevant standards. When this is complete, witnessed and documented, the plant is ready to be handed over for further installation and commissioning of the related machine parts, that is, of the accelerator, target and instruments or parts thereof.

Commissioning requirements and methodology

The successful implementation of any installation plan is dependent on a properly conducted commissioning procedure prior to handover. Conventional Facilities will already have ensured during the design stage that the requirements and extent for the commissioning work have been clearly defined. Factory acceptance tests and other special demands, if any, will have been specified. BLED databases will have been populated and BIM guidelines will have been followed. The specification and design drawings will address and incorporate appropriate facilities for commissioning. Subsequently, the system installation subcontractor during the construction phase will be required to develop and submit a detailed commissioning method statement for each system, specifying which tests are to be performed and how they will be carried out and documented.

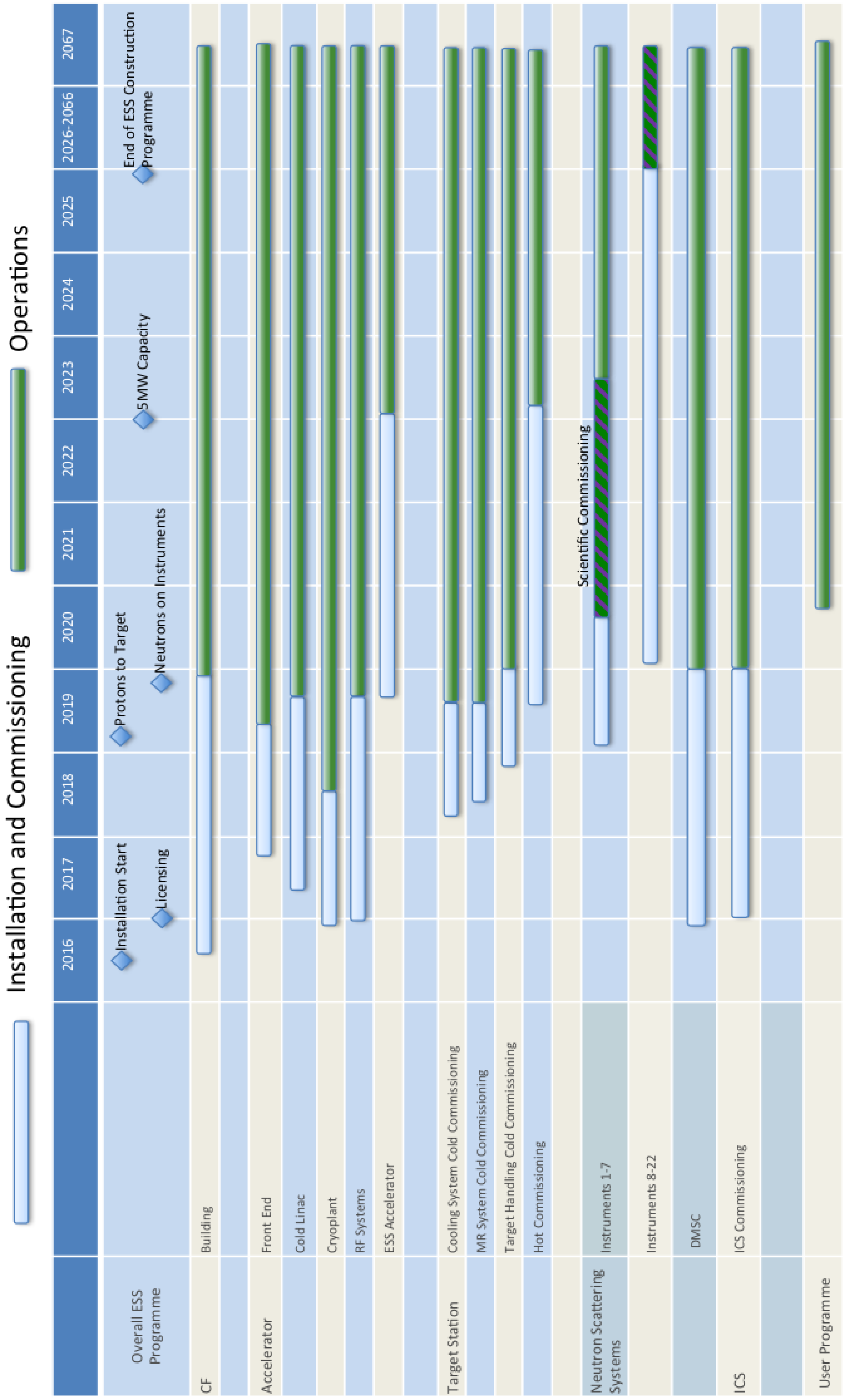

Figure 9.4: High level timelines for system commissioning during the transition to operations. Both installation and commissioning activities, and operations activities fall within the operations phase of the programme.

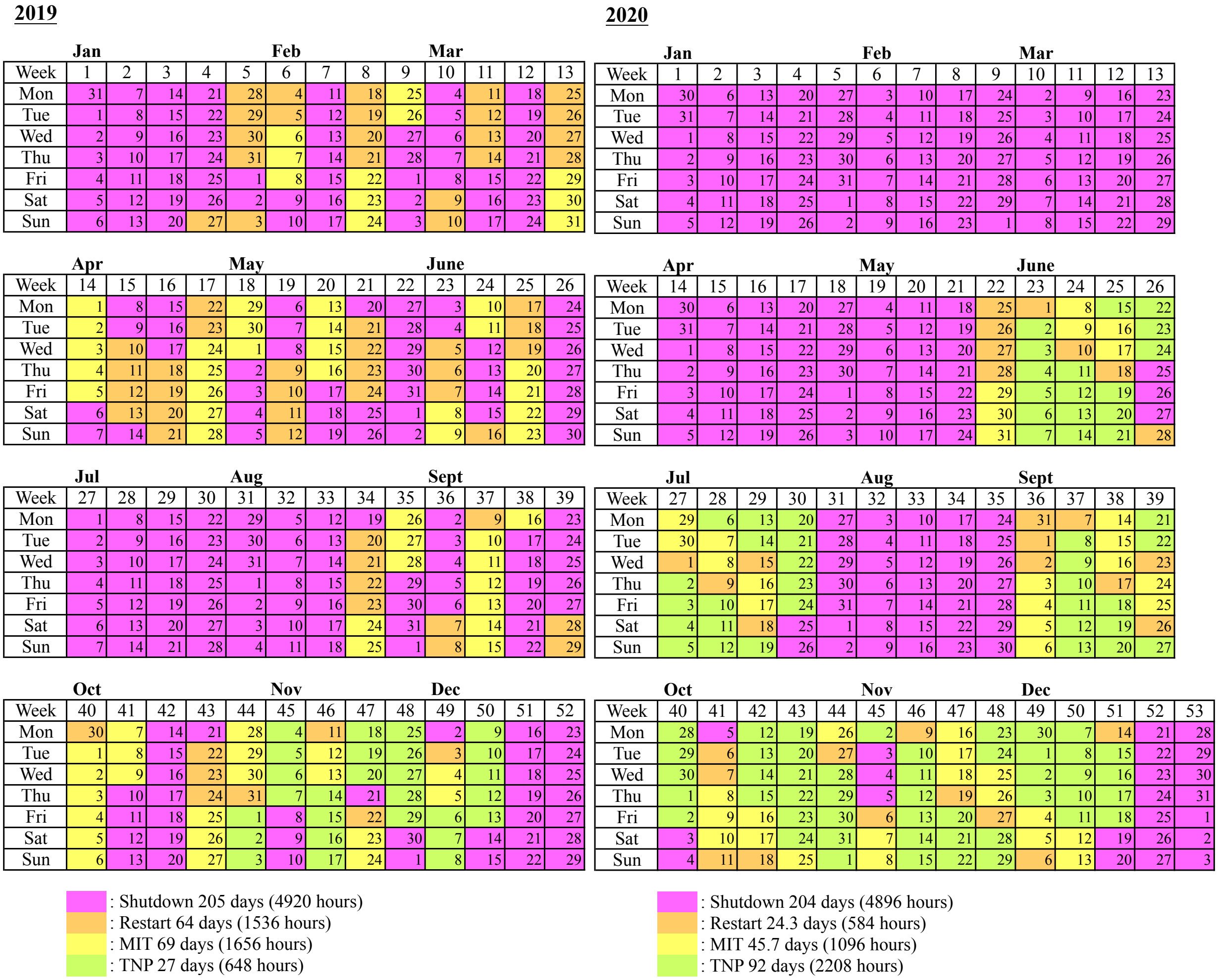

Figure 9.5: Provisional beam schedule for the year when first neutrons are produced (2019), and for the first year in the operations phase (2020). The schedule indicates when machine is shutdown (magenta), when its is started (orange), when operated for machine studies (yellow) and when it is producing neutrons (green). During power ramp-up and early commissioning stages the availability will be low and reliability poor. During the long shut down in the winter-spring the high-β cryomodules will be installed and most likely also instrument beam ports will be opened/installed.

Commissioning team

The conventional facility commissioning team will include a BMS subcontractor engineer, a subcontractor representative engineer, an ESS specialist consultant engineer and an ESS installation coordinator. Additional personnel, including system specialists, will join the team as and when required.

Staged commissioning

In order to line up with time schedules for commissioning of the various machine parts, conventional facility commissioning will be flexible and will be performed step-by-step. Conventional facility installation will be logistically complicated, including temporary installations due to late completion of permanent infrastructure. Details will be developed as machine requirements are consolidated. A tentative conventional facility commissioning time schedule is shown in Table 9.1. Generally the commissioning works will be divided into adjustments and tests on completion. Tests on completion are divided into two stages. First, functional tests verify that all requirements on a system are met when working in a stand-alone mode. Second, coordinated tests verify that all requirements on a complete plant or building are met when all relevant systems are in operation and are fully interconnected. Responsibility for carrying out adjustments

Period	Facility
Summer 2015 to autumn 2016	Accelerator building
Spring 2017 to winter 2017/18	Target station building
Summer 2017 to winter 2018/19	Instrument buildings
Summer 2019	Offices
Summer 2019	Laboratories
Autumn 2019	Canteen and guest house

Table 9.1: Tentative conventional facility commissioning schedule.

and conducting tests rests with the subcontractor. It is the task of the subcontractor to prove that the system installation is in accordance with the specification and all relevant norms and regulations. All tests must be be documented in test records and these records will be a part of the handing-over documentation submitted by the subcontractor.

Installation tests and other prerequisites for the commissioning works already will have been executed during system installation works and will be governed by the respective quality system of the subcontractor or, if works have been executed directly by ESS, by ESSs own Quality Manual. Any such quality system will at minimum comply with AMA (*Allmän Material och Arbetsbeskrivning*) [578]. These prerequisites include (but are not limited to) installation inspections including hidden works; flushing and leakage control of all pipe works; cleaning and leakage control of all ventilation ducts; insulation resistance test and colour coding of all electrical installations and cable works; labelling of all installations; and ensuring that the building envelope or relevant part thereof is completed. Assemblies, apparatus and components – whether separated or composite – must meet requirements on design, specifications and CE marking in accordance with the European Machine Directive SS-EN ISO 12100:2010 and Swedish law (SFS 2011:791) as well as the Work Environment Authority regulations (AFS 2008:3 and AFS 2009:5).

Documentation that must be available includes as-built drawings, an extensive photographic and video database, and operation and maintenance manuals. Operating procedures will be developed and validated as part of commissioning with associated training for ESS staff that will be responsible for operating the systems. Consideration will also be given to developing a 3D data base for all structures and components based on as-built conditions. When the above conditions have been fulfilled for a building and the service systems in it, the building can be declared "ready-for-occupancy". Note that SNS negotiated an intermediate completion stage called "ready for [machine] installation", which allowed storage and early installation work to begin before a building was "ready-for-occupancy".

9.4 Accelerator

The installation of accelerator and target components will begin as soon as occupational readiness has been achieved and buildings and the installation of infrastructure such as electricity, water, ventilation and communications has been completed. The different subsystems will be installed and taken into operation in stages, each with readiness reviews, ensuring that all dependencies of one subsystem on another are fulfilled and verified. Completion of the readiness review, and follow-up on any review recommendations will take place before beam commissioning begins. Detailed commissioning plans will be written for all systems during the construction phase, at the same time that all necessary procedures, software tools and instruments are developed. Commissioning plans will describe the goals for the commissioning stage and the activities needed to achieve these goals.

Staged commissioning

The commissioning plan is based on the concept of a stepwise completion of the infrastructure and conventional facilities. In order to use the available time in an efficient manner, the linac tunnel, the klystron building and the infrastructure are made available for commissioning in four stages, including supporting infrastructure such as electrical power, cooling water, piping for cryogenic fluids, et cetera. Each stage allows the complete installation of a section of the accelerator and its associated support equipment. Section commissioning will take place while work on the buildings for the next stage continues to take place.

The four stages, which also correspond to portions of the accelerator where beam-stops are planned for tuning purposes during operation, are:

1. The front-end: ion source, LEBT, RFQ, and MEBT.
2. The drift tube linac
3. The superconducting linac with spoke resonators, all medium and high-β elliptical cavities.
4. The high energy beam transport and final approach to the target.

The initial stages cover relatively small sections of beam-line, but offer an early opportunity for integrated operation of systems needed for production of beam. Lessons learnt in this early period will facilitate commissioning of the more involved later commissioning stages. This is a primary motivation for striving for early stages of beam commissioning. Stages 1 and 2 require that electrical power, cooling water and other services are installed. Cryogenics are not used until stages 3 and 4. Cryogenic plant commissioning for the accelerator is thus part of stage 3.

The accelerator is planned to be taken into operation already after the commissioning of the medium-β section, with a temporary drift section installed for the high-β section. The energy above 600 MeV will be sufficient to drive the spallation reaction with a power of about 1 MW to 1.5 MW and produce neutron beams. The cryomodules and associated RF equipment for the high-β section can then be installed during the first three years of power ramp up. The installations would be carried out mainly during the long annual shutdowns. The staged installation of the high-β cryomodules affects the power ramp-up only marginally and it reduces schedule risk substantially.

Beam dumps and shielding

The beam destinations for the stages described above will have insertable beam stops for use during beam study periods that can also be used for commissioning. The ionising radiation created by the beam on these beam-dumps will be appropriately shielded with a temporary wall so that installation and construction work may continue downstream. The insertable beam stops will receive beam up to the nominal energy (at that position in the accelerator) and at the nominal current, but the beam pulses will be much shorter than nominal, down to 10 to 20 μ s, and the pulse repetition rate will be much lower, so that radiation can be kept at acceptable levels. It will still be possible to verify full operation of a majority of subsystems during each of the three commissioning stages, however, because the instantaneous beam power will reach its nominal value. Full power beam commissioning will be performed when the spallation target is in operation, since the accelerator itself will not be equipped with a beam dump that can handle the full average power of 5 MW

Testing before installation

Hardware components will arrive from factories and laboratories around the world for installation. All major components will be tested before they are sent to Lund. This includes ion source, RFQ, DTL tanks, cryomodules, RF sources and many other items. Linac structures will be tested at dedicated facilities at several collaborating accelerator laboratories. The normal conducting accelerator up through the RFQ will be tested for an extended amount of time, on the order of 6 months, at full power and with beam before it is delivered to Lund.

There is a comprehensive plan for testing the linac RF and cryomodule components. Manufacturers will test the RF klystrons as part of the acceptance criteria, and the high power modulators will be tested in place as they are installed in the klystron gallery in Lund. Testing is also planned for the superconducting cavities and cryomodules. Cavities will be tested in vertical tests to assure that they meet the design criteria, including an appropriate margin to account for the typically higher vertical test results compared to operation in a final horizontal assembly. Cavities that do not meet specifications will be further processed as needed before assembly into strings used for cryomodule fabrication. The baseline plan calls for cryomodules to be tested at high power at test stands in Uppsala (352 MHz structures) and on-site in Lund (704 MHz elliptical structures). If the cryomodules do not meet specifications, they will be shipped back to the manufacturer for repair.

If the equipment delivery and installation schedule does not permit high power testing and repair of cryomodules that do not meet full specification, another strategy is to install the cryomodules in the tunnel as they arrive, forgoing the high power RF test, as was done at SNS. In this approach, some installed cryomodules may need to be removed and upgraded later. The superconducting linac design is quite flexible and can accommodate reduced superconducting cavity performance.

Under-performing installed cryomodules still provide some acceleration and additional neutron production. Also, because of the early cryomodule installation, the supporting RF systems will be subjected to operational experience sooner. Cryomodule removal, upgrade and re-insertion in the linac would occur during the power ramp-up period of 2019 – 2025. Spare cryomodules for each of the families are planned, to facilitate this process, and missing cryomodules (taken out for repair) can also be tolerated for most of the linac. Also, *in situ* plasma-processing cavity remediation techniques are under development at SNS for the purpose of reducing the field-emission limitations, which is by far the most common type of superconducting cavity operational limitation.

Commissioning with beam

Commissioning here means the initial operation of the linac sections with beam, after final installation activities in Lund. System experts will develop plans and test each of the supporting technical systems individually, prior to beam commissioning. It is foreseen that a readiness review with the Radiation Safety Authority will occur prior to each stage of commissioning to ensure that adequate personnel and machine protective controls are in place. The reviews will also cover individual system preparations and tests. In each commissioning stage, an important part of the commissioning plan includes testing the machine protection interlock systems with tightly controlled beam spills, to verify their integrity.

Stage 1: Front-end

The first commissioning stage encompasses the ion source, low energy beam transport, radio frequency quadrupole, and medium energy beam transport. This section is about 10 m long altogether. Although some of this equipment will have been run with beam at collaborator sites, this will be the first beam acceleration at Lund. A key goal of this commissioning stage is integrated operation of all systems that the ESS will use for the acceleration and control of beam. This portion of the accelerator does not require tunnel enclosure, as the radiation levels will be minimal. In addition to verifying the integrated operation of the ESS sub-systems (timing, machine protection, controls systems, magnets, RF, vacuum, cooling etc.), beam quality will be quantified with a variety of measurements. The beam instrumentation group will test beam position monitors, beam current monitors, emittance and profile-measurement systems. While much of the RF equipment will have been tested before commissioning, the RF group will verify that the low-level RF system works properly with beam. This commissioning stage will also be the first opportunity for high level software tools to be exercised, for instance trajectory correction, RF phase scans and transverse matching.

Stage 2: Drift tube linac

The drift tube linac (DTL) will be installed in the linac tunnel, with supporting RF equipment in the klystron gallery. It comprises about 30 m of beam-line. The beam destination is a planned beam stop in a differential pumping section between the warm linac and the cold linac. This stage will involve the first significant beam acceleration. The primary beam tuning in this stage will be setting the RF amplitude and phase of the DTL klystrons. This will also provide an opportunity for testing system changes implemented as a result of lessons learnt from the first stage of commissioning, and possibly further refined.

Stage 3: Superconducting linac

The superconducting linac includes the spoke, medium-β and high-β cavity family types, and drift sections provided for future energy upgrade. It covers an energy range of about 80 MeV to 2500 MeV and corresponds to about 400 m. Beam will be directed to a straight-ahead tuning dump at the end of the linac, which includes a small portion of the HEBT system. Using a beam-line without bends greatly simplifies the beam tuning over such a wide energy range. The cryogenic system will be needed for this stage of commissioning and this stage also represents the first large-scale use of high power RF with beam. Before beam commissioning commences, the RF group will qualify each superconducting cavity, to determine its safe operational limits (without beam) in the actual ESS machine environment. This step will identify upgrade needs for the superconducting RF equipment.

The primary beam tuning activity will be to set up each RF source with respect to the beam. Transverse matching at the lattice transitions between cavity types will be done, and the beam quality at the final energy will be measured with profile measurements. Running the superconducting RF with beam will also provide an opportunity to test the feedback and feed-forward systems of the low-level RF systems to compensate for the beam loading effects. Also, this will be the first opportunity to run beam at high enough energy to get meaningful response from beam loss monitors, which are a critical protection element.

Stage 4: High energy beam transport and target approach

The final beam commissioning will take place through the high-energy beam transport (HEBT) system to the target. Prior to commissioning, the target systems will need to be tested, and the systems reviewed and approved for low power beam readiness. This includes the target and all supporting systems such as the cryogenic moderators, shutters, neutron choppers, beam dump and initial beam instruments. Remote handling methods for critical systems will have to be demonstrated. In addition to delivering the beam to the target, this transport line has the important function of qualifying the beam properties as suitable for high power delivery to the target. These systems will be commissioned at low power, and procedures will include provisions for ensuring proper beam position, peak beam density, and allowable beam-halo levels at the target (halo here refers to the radial extent of beam at the periphery of the target). Beam diagnostics to be employed in this stage include profile measurements, beam position monitors, beam harp device, halo measurement systems, and imaging systems for the beam at the vacuum window and at the target.

Beam power ramp-up

A beam power ramp-up period will follow the initial delivery of beam on target, after a review of operational-readiness-for-high-power is performed by the the Radiation Safety Authority.

The average proton beam power on target is the product of the beam energy, the beam current, the beam macro-pulse length and the pulse repetition rate. Increases in average beam power will be modulated primarily by incrementally increasing the repetition rate and the macro-pulse length. Initially, the pulse repetition rate will be increased, reaching 14 Hz after about one year of operation. This will allow the neutron instruments to be commissioned at their final 14 Hz data acquisition rate as soon as possible. Also, some accelerator performance issues, such as Lorentz detuning, will be become more severe as the pulse length increases, and increasing the pulse length may require more development time than increasing the repetition rate. Pulse length issues will be investigated during beam study periods early on, at low repetition rates. If the final beam energy is below the 2.5 GeV design level due to cryomodule performance, the poor-performing structures will be swapped with spares, and re-worked in the planned superconducting RF facility discussed above, during the period of 2019 – 2025.

Another important issue during the initial power ramp-up period is gaining an understanding of the activation of the in-tunnel beam-line components from beam loss, and its impact on maintenance. Translating the beam loss monitor measurements during operation into residual activation of in-tunnel equipment after beam shut-down is largely an empirical exercise. The previously described machine protection qualification during the initial beam-commissioning period serves the purpose of assuring prompt protection against machine damage. However it is possible to cause significant residual activation of tunnel components with beam loss levels that do not cause equipment failure. To protect against buildup of higher than expected residual activation, limits on slower, time-averaged beam loss measurements will be set based on activation measurements taken in the tunnel. This effort will also involve optimisation of the placement of loss monitors to ensure that beam loss monitors adequately cover all beam-line areas. The operational run periods between residual activation measurement surveys will start at a frequency of every few days, and be extended to once a month after four years (2023). The beam power increase from one run to the next will be limited to less than a factor of two initially, and reduced to increases in the range from 10% to 20% as the final 5 MW power level is approached.

As 2025 approaches, a primary operational constraint will be the 95% reliability goal. In particular, downtimes covering fractions of a day or more are particularly disruptive for users. Many users will only

System	Subsystem	Test
Target	Shaft and drive	Run at up to 25 Hz.
	Target segments	Leak test at pressure.
	Target Safety System	Demonstrate trip signals generated for all defined cases.
Primary helium loop	Pump, heat exchanger, filter	Pressure and flow tests without target.
	Full loop with target	Full operational test without heat.
Target secondary loop	Nitrogen loop	Pressure leak tests, full flow testing without heat.
Moderator	Helium refrigerator	Full heat load test with resistive heater.
	Hydrogen loops	Loop testing without moderators.
	Hydrogen loops	Loop testing with moderators.
	Hydrogen loops	Off normal and venting tests.
Water loops	Reflector, PBW, shielding loops	Pressure decay leak testing.
	Reflector, PBW, shielding loops	Fill and drain testing.
	Reflector, PBW, shielding loops	Full flow testing.
	Inert cover gas system	Demonstrate design gas flow rates, I&C.
Gas	Monolith Helium system	Monolith helium fill and gas analysis.
	Helium distribution	Operational check of all warm helium systems.
	Nitrogen distribution	Operational check.
	Vacuum	Operational check and leak rate measurements.
	Activated off-gas	Leak check, flow tests to stack or holding tank.
Monolith	Primary shutters	Test cycle times, safety system performance.
	Neutron beam windows	Test leak tightness of all windows installed on beam lines.
	Beam dump cooling	Test flow rates and leak tightness of dump.
Remote handling	Hot cell operations	Test all operations that require full remote handling for beam operations > 100 kW.
	High bay operations	Practise component replacement.
	Waste handling	Test target disposal method.
Instrumentation & control	All subsystems	Demonstrate proper operation and integration with overall ESS system.

Table 9.2: Stage 1 target station commissioning tests, without beam.

be at ESS for two to three days, and will have invested considerable time into planning experiments. If reliability is threatened by operation at higher power, the beam power will be limited to provide reliable operation. A key effort for the accelerator system owners during the period 2019-2025 will be to identify and remediate equipment issues that cause downtime. Also, exploiting the full flexibility inherent in a superconducting linac design to maximise machine reliability will be useful for achieving 95% reliability. For instance, it will be possible to continue running beam with an RF cavity or klystron offline, or even a high voltage convertor modulator (powering two RF sources) offline, over much of the linac. Model-based rapid adjustment of a superconducting RF linac setup to adapt to a failed cavity has been shown to work [615]. Developing fault recovery tools to quickly adapt the accelerator setup to work around failed components will be a major high level controls effort in the period 2019-2025.

9.5 Target station

The time frame for accelerator commissioning will be rather long. The target station will be the last major machine component to be commissioned. Target commissioning will demonstrate both the appropriate performance and also the safe functioning of the target systems during operation (with beam on target), and also during maintenance. Operating procedures will be validated and documented and ESS operating staff trained. The commissioning will include the neutron production systems (target, moderators and premoderators, proton beam window, etc.), the ancillary systems and the safety systems (shielding, confinement barriers, etc.).

Stage 1: Commissioning without beam

The first stage of target commissioning will be performed without any beam on the target, allowing for the correction and adjustment of parameters as necessary. A preliminary set of pre-beam commissioning tests is given in Table 9.2.

This stage will proceed in parallel with accelerator commissioning, up until beam commissioning on the tune-up beam dump system. Systems will initially be tested separately, followed by integrated system testing with multiple systems including the overall instrumentation and control systems using documented operating procedures. Physical and functional interfaces with the accelerator, instruments and conventional facilities, which can be tested without beam, will be verified to be acceptable. Handling procedures and tooling for components such as the target, which will be activated beyond hands-on levels even at low initial beam power levels, will be fully demonstrated. Some safety functions will be tested in this stage (usage of portable sealed sources, etc.), without creating any active inventory. Proper operation of all safety systems required for beam operation will be tested and verified. Responsible engineering work package managers will define the required testing for their systems.

Stage 2: Commissioning with low power beam

The second stage of target commissioning starts when the proton beam is first delivered to the target. A preliminary set of low power commissioning tests is given in Table 9.3. The pace of the low power ramp up may be limited by activation and contamination levels, in those cases in which "hands-on" levels are desired for unexpected maintenance on systems such as primary loops and off-gas systems. Procedures for the second stage of commissioning are still being defined.

Irradiation will start with very low power on target (of the order of 1% of the nominal 5 MW). Some low power measurements will be performed before progressively increasing the power, with intermediate stabilised plateaus. In this phase, first neutrons will be measured at the beam lines. Extensive radiation surveys will be done to identify any shielding weaknesses. Some special tests can be done at this low power, involving the safety interlock systems; for instance safety systems related to the beam profile shape can be tested by reducing the beam spot size (something that can be done only at low power). The functioning of systems like the heat removal system, or the cooling loops, can be tested and compared with predictions from calculations, and with previous measurements done during the tests. While slowly increasing the beam power, efforts will concentrate on the precise measurements of fluxes, on additional tests of the cooling loops and heat removal systems, on radiation mappings, and on investigating the performance and safety of the target station, to match the expected operating and licensing requirements.

Target beam commissioning includes tests and qualifications of the accelerator to target interface. Beam profile measurements will be performed for both accelerator and target. The correct functioning of the beam profile monitors is essential, as the peak current density will be controlled at all times during irradiation. First neutrons will be detected by the instruments and moderator neutronic performance will be measured and compared to acceptance criteria. Target station monitoring will be tested by validating and understand control signals from the target, such as pressure sensors and target temperature measurements. When possible, physical parameters will be measured directly by independent redundant systems through the target control system, in order to cross check and validate the normal output signals.

Radiation protection monitoring will be performed at certain key points of the facility, including dose measurements at the beam exits and radiation gas monitors. Spallation products (volatiles and possibly non-volatiles) will be measured in the gas systems using conventional spectroscopy methods. One surprise in SNS was that the xenon and krypton would adsorb on dust and also on the gold filter used to remove mercury from the helium cover gas, which gave unexpectedly high dose rates in unexpected locations. For ESS there might also be surprises from activated dust transport. There should also be an effort to evaluate tritium production and transport. Another area of interest would be the production of free hydrogen and oxygen in the water loops by radiolysis.

System	Subsystem	Test
Target	Shaft and drive	Run at 25 Hz.
	Target Safety System	Demonstrate front end trip for a loss of rotation.
	Beam diagnostics	Establish beam density profile and location on target segments.
Primary helium loop	Pump, heat exchanger	Compare measured temperatures with predictions.
	Filter system	Measure activation in filter room due to trapped dust.
Target secondary loop	Nitrogen loop	Compare measured temperatures with predictions.
Moderator	Full loop	Compare measured temperatures and pressure fluctuations with predictions.
	Neutronic performance	Measure brightness and time structure from both moderators.
	Transfer lines	Measure vacuum levels with beam, and measure activation.
Water loops	Reflector, PBW, shielding loops	Compare measured temperatures with predictions.
	Inert cover gas system	Measure gas production by radiolysis.
Gas	All subsystems	Confirm normal operation with beam.
	Activated off-gas	Measure dose rates and stack releases. Measurements of spallation products and comparison with predictions.
Monolith	Shielding	Survey all areas after each significant increase in beam power.
	Beam dump	Compare measured temperatures with predictions.

Table 9.3: Stage 2 target station beam commissioning tests, with low power beam.

Safety barriers for the internal confinement of radioactive contamination will be tested, along with zoning confinement for helium and hydrogen hazards. These functions are assured by the HVAC and confinement devices (penetrations). Handling systems will be tested before active beam commissioning. If possible, remote handling systems will be used during initial installation for the target, proton beam window and moderator/reflector plugs. Hot cell operations that will be done remotely will be tested before beam operations. The correct functionality of key waste handling operations will be demonstrated. The interdependences of different target control sub-systems will be tested, including transient responses – for example, moderator loop control system response to pressure transients. Protective actions will be tested during integration with the overall accelerator control system, including alarm response procedures. Target protection system and safety-related beam shutdown operations will be tested before first beam on target, and also at low power.

Very low power target commissioning may be performed without some ancillary systems, but all ancillary systems must be fully operational well before full power operation.

Stage 3: Beam power ramp-up

As discussed in the accelerator section, following the initial target beam delivery, there will be a progressive ramp-up of the beam power (energy and repetition rate). The target systems will have to withstand operation at full power. This includes, for instance, the cryogenic loops, which will have to operate at maximum heat deposition in the moderators, close to 10 kW per module. In general, most of the tests listed in Table 9.3 will be repeated at full power to arrive at routine operation of the target. A key aspect concerns safety, related to activation levels, shielding, and functioning of containment barriers. Radiation levels and the residual neutron field outside the shielding will be monitored at full power.

9.6 Instruments

For the neutron scattering instruments, the transition from the construction into operations has two phases – cold and hot, as indicated in Figure 9.6.

Stage 1: Cold commissioning without neutrons

The end of the construction of an individual instrument is marked by a successful completion of the "cold commissioning" phase, after which all instrument components function as anticipated for operations, but without receiving neutrons from the target. High level instrument systems and tests are indicated in Table 9.4. The end of cold commissioning for an instrument will be marked by a "readiness-for-operations" document, approved by an appointed operations manager. The individual beam shutter cannot be opened prior to this approval. The main focus of this phase is to ensure that all components and sub-systems of an instrument system work according to specifications; that communication channels and exchange of signals between accelerator and target are established and working; that safety-relevant systems such as safety interlock systems work according to design and that their functionality complies with local rules and regulations.

Stage 2: Hot commissioning with neutrons

Once an instrument is ready for "hot commissioning", the focus is on testing it under real operational conditions with an emphasis on finding and rectifying bugs and issues, and on keeping pace with the proton beam power ramp up. Radiation surveys will be carried out at very low power on target. During this period, extensive radiation surveys will be done to identify any shielding weaknesses as the accelerator power is increased to its final operating power of 5 MW. The exact details for the hot commissioning of a neutron scattering instrument will be detailed in the *Instrument Commissioning Schedule.*

In order to move the instrument from the commissioning phase into the operational user mode, further administrative requirements include the availability of two database-driven systems, one of which accepts proposals including user, sample, instrument, sample environment and scheduling information, and the other of which tracks samples on their way through the facility, from arrival to check-and-release following radiation protection procedures. Neutron scattering personnel will begin the transition from construction into operations in 2019, in accordance with the construction schedule. Pre-operations – the beginning of operations and use of laboratories such as sample environment, neutron optics or detectors – will already

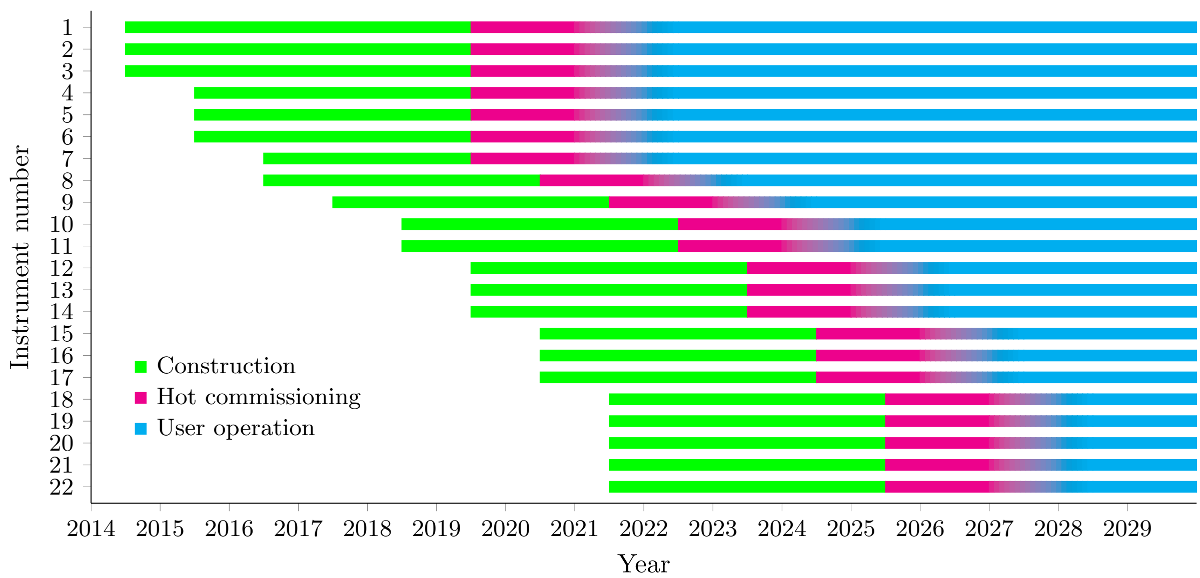

Figure 9.6: Instrument construction schedule. The construction period for each instrument (green) ends with "cold" commissioning, followed by a period of "hot" commissioning (red) before the instrument moves into normal user operation (blue).

Sub-system	Test
Choppers	Receive signals from accelerator timing system. Feedback to instrument motion control, data acquisition and instrument control system.
Guides	Measure vacuum levels.
Motion stages	Feedback to instrument motion control, data acquisition and instrument control system.
Safety interlock system	Feedback to instrument motion control, data acquisition and instrument control system. Communicate with machine protection system.
Detectors & neutron monitors	Feedback to instrument motion control, data acquisition and instrument control system.
Data reduction	Access raw data from data acquisition system and conversion from instrument coordinates to physical coordinates.
Data analysis	Access and analyse reduced data sets.
Data storage	Archive and store data in accordance with data management policies.

Table 9.4: Basic instrument systems tests during the cold (construction) and hot (operations) commissioning phases prior to user operation (operations), for instruments 1 to 22. Cold commissioning: Simulated signals to test detector systems or using portable neutron source, if appropriate licensing is provided, with instrument shutter closed. Instrument must be fully functional. Hot commissioning: Using spallation neutrons coming from the target with instrument shutter open. Instrument must be fully functional.

have commenced in 2018, depending on when such laboratories are handed over as “ready-for-occupancy” by Conventional Facilities.

9.7 Integrated control systems

A functioning control system is a pre-requisite for the commissioning and acceptance of all devices (accelerator, target, conventional facilities and instruments) for the operations phase. Core components of the control system will be tested and accepted before installation of the accelerator, target and instruments begins. High-level applications that will provide the integration of all devices via a uniform look-and-feel to test and accept devices before and during beam commissioning will be developed in parallel with the installation and commissioning of devices during the construction phase.

The core control system components are global timing, system services, machine protection and personnel protection. The global timing system provides clock synchronisation for all devices. System services include management of alarms, the logging and archiving of data from process variables, management of control system configuration settings and the post-mortem service for detailed analysis of events which have caused the machine to shutdown or to stop proton beam production.

The machine protection system (MPS) is a non-safety class system whose purpose is to protect the machines equipment from damage due to malfunctioning components (of equipment) and due to non-nominal and/or critical beam losses. If the MPS detects critical or non-nominal machine conditions, the proton beam will be switched off and further beam injection will be inhibited until the origin of the failure has been eliminated and further beam operation is considered to be safe. The personnel protection system (PPS) is a safety-class system whose purpose is to protect personnel against unnecessary radiological exposure from the ESS machine, electrical shock hazard and other dangerous phenomena (such as loss of oxygen in the tunnel, helium release, etc.). If personnel enter into areas where exposure to radiation is possible, no beam operation will be allowed and will be interrupted immediately.

All these systems must be tested and operational for the installation and commissioning of the machine equipment with (and without) beam and will be fully exploited and integrated before the ESS operation phase starts. An external review of the final control system is foreseen before formal operations can begin, encompassing all aspects of the control system so that the necessary levels of security, safety, integration, and reliability can be assured. If other control systems for some sub-systems are identified at this time, which are not (yet) part of the ICS, these systems will be tagged for integration.

Operational modes and support from MPS and PPS

The different configuration settings for all beam and machine modes will be located in a common database, which is embedded in the ICS. The matrix shown in Figure 9.5 provides an overview of the currently foreseen operational modes, i.e., of the various machine and beam mode combinations.

MPS and PPS must protect the machines equipment and ESS personnel, but at the same time, these systems must support operational flexibility which is required during the installation, commissioning and operation phases of the ESS machine. In this context, the ESS machine consists of the accelerator, target station, ICS, energy platform, and conventional facility suite layout. It is important to define sequences of actions to be taken in order to bring the machine, for example, from a state of maintenance to a state in which it produces neutrons at full power; i.e., to operate the machine means to bring the machine into different *states*. Several *operational machine state*s have been identified, including maintenance, machine development, restart, and full power neutron production among others. The states consist of several operational modes, where each operational mode represents a combined set of one beam and one machine mode.

A machine mode refers to a specific machine configuration and provides an overview of whether the machine is powered or not, whether the machine (or parts of it) can be accessed by personnel or not, etc. Additionally the machine mode defines the source and the intended destination of the proton and neutron beams within the machine layout. Before starting any beam-based operation, all transport systems must be ready and validated for the setting. The beam permit system, which is part of the MPS ,will perform this validation. Different intended destinations for the proton beam are, for example, interceptive stops such as Faraday cups, the tuning dump line or the target station.

The machines equipment will be installed and commissioned stepwise and the machine modes will be set up according to these different steps, allowing for high operational flexibility. Especially during installation and commissioning, it must be possible to install equipment, for example, in the cold LINAC while performing beam-based tests in the warm LINAC. In order to do so, the machine modes will also be individually applicable for each segment of the machine and not for the full machine only. For example

BEAM-MODE.qualifier	**MACHINE-MODE.qualifier**												
	SHUTDOWN.segment	COOLDOWN.segment	ACCESS.segment	WARMUP.segment	CALIBRATION.segment	RECOVERY	ABORT	NAHZ.segment	STANDBY.segment	SETUP.segment	PREPARE-TARGET.segment	PRODUCTION.power	STUDIES
NO-BEAM	x	x	x	x	x	x	x	x	x				x
PROBE-BEAM.segment										x			x
SETUP-BEAM.segment										x			x
PREPARE-PHYSICS-BEAM											x		x
STABLE-BEAM.power												x	x
BEAM-TRIP												x	x
BEAM-ABORT						x			x	x	x	x	x

Table 9.5: Matrix of beam-modes and machine-modes. The *segment* mode qualifier refers to a part of the machine. For example STANDBY.LINAC is true if the LINAC is ready for beam injection after it has been fully tested. The *power* mode qualifier has values such as LOW-POWER and HIGH-POWER. A cell marked with a cross “x” indicates that a beam-mode and a machine-mode have the potential to both be simultaneously true. For example, the SETUP-BEAM beam-mode cannot be true if the ACCESS machine-mode is true.

ACCESS is a machine mode, which can be ON for the LEBT (i.e. access is allowed in the LEBT segment) but OFF for the DTL (i.e. access is not allowed in the DTL segment): ACCESS.LEBT=ON and ACCESS.DTL=OFF. If access rights are violated, the access permit will be removed and possible beam operation will be interrupted by the PPS. The machine mode SETUP validates the intended destinations of the proton beam: SETUP.DTL.FC.4 indicates that the proton beam will be stopped in the fourth Faraday cup in the DTL.

A beam mode is defined through specific beam parameters, such as peak current, pulse structure, beam power, pulse repetition rate, etc. Several different types of beam modes are needed in order to commission and operate the machine with beam in a safe way: beam parameters for the "probe beam mode are chosen such that the beam is considered to be safe. A safe proton beam can reach any destination within the accelerator and target station layout and has no potential to damage the equipment. The probe beam settings can be different for the LINAC (ending in the tuning dump line) and the A2T line (ending in the target station). Usually, the probe beam modes will be used in a first step of beam-based operation.

In a second step, the setup beam modes will be used to tune the accelerator and take measurements for diagnostic purposes as well as for the preparation of the target station for full power neutron production. After the accelerator and the target station have been prepared for full power production, the so-called stable beam modes will be used to indicate a stable neutron production at medium or full power to the different users. There are two more beam modes foreseen: beam trip and beam abort, where "beam trip reflects a short interruption of the proton beam due to a minor problem of the machine and "beam abort indicates a serious problem resulting in a longer interruption of beam and neutron production. The beam permit system permanently crosschecks the beam parameter settings (for example, verifying that the voltage on specific magnets is as expected for a given condition and mode) and if non-nominal conditions are detected, beam operation will be interrupted by the MPS.

Controls commissioning strategy for device integration

The major structures in the facility – Accelerator, Target and Instruments – will be brought online in stages during installation and commissioning. At every point in this process the control system for each of these devices will have to be tested individually. The integration of these devices into the main control system will occur as each of these devices is commissioned. The Controls Group will have an Integration Support Group working in tandem with machine and neutron instrument personnel, to provide the necessary support. The schedule for final control system integration will follow along with the end of commissioning of the major structures. Following this step-by-step process, the ICS will be built for the entire facility. Major sub-systems such as Cryogenics and Vacuum (and others) will be developed by outside contractors and delivered to ESS. The ICS project team will accomplish the integration of their control systems into the main Control System in time for the use of these systems for commissioning of the Machine and Instruments.

Conventional facility controls

Electrical Power, Heating, Ventilation, Air Conditioning, and Water Systems as well as Safety and other sub-systems provided by Conventional Facilities will be integrated early in the development of the Control System, as they are also pre-requisites for the installation of the Machine and Instrument devices. The schedule for the integration of these control systems will be determined by the delivery time of each sub-system.

Main control room and data centre

The main control room will be the place where operations activities will be centred, and every part of the machine will be controlled and monitored from this central location without exception. Neutron Instruments will also be monitored from the main control room, but since neutron scientists will need to be near their sample environments and data acquisition hardware, satellite control areas will exist. These satellite areas will contain the systems needed for control and monitoring of instruments and sample environment, which in most cases will only be monitors and user stations. In addition, data acquisition for the experiments may also be controlled from these areas as the electronics for the experiments will be located as close as possible to the sample environments in most cases.

A secure and local data centre supports the control systems main control room where servers for both the control system and immediate post-processing of data from the experiments will be housed. High-speed and secure networks and data storage capabilities will provide the necessary computing infrastructure for both machine and instrument operation. Data acquisition from the experiments will pass through this data centre on its way to permanent storage and analysis at the DMSC facility in Copenhagen. Only authorised personnel will have access to the main control room and related networks.

The control room will be built in at least two stages. During installation and commissioning of the machine and the first instruments, a temporary control room will be built. The temporary control room will serve the role of the main control room until the building where the main control room will be housed is completed. Since the main control room will not contain any hardware, only monitors and control stations, it will be possible to move operations from the temporary to the final control room relatively easily as both rooms will exist in parallel for a time until the temporary control room can be decommissioned. The final control room will be equipped with a kitchen, sleeping and rest rooms, showers and a reception.

9.8 Operational lessons learnt from other facilities

SNS target system reliability

In general target systems achieved high reliability with only a few exceptions. A number of factors that are believed to have helped are:

1. Simplicity was emphasised in design.

2. All support systems and shielding were designed for full 2 MW operation.

3. Operating technician staff were in place for installation and commissioning and were very well trained and had well developed normal-operating and alarm response procedures.

4. A full-scale prototypical primary mercury loop was constructed and operated leading to many improvements in the loop and target design. For example, extreme flow-induced cavitation was found with the first target design, resulting in a redesign.

5. A prototypical cryogenic moderator loop was tested during preliminary design, which resulted in changing the type of circulator and also validated the control system design with cold accumulator to reduce pressure fluctuations.

6. Redundant pumps were used for all water loops with automatic switch over.

7. Extensive remote-handling testing was done both during early design and for over six months on-site prior to first beam on target

SNS target system operations

1. Primary pump continuous testing was only done for a few days and did not identify a problem found during the first long-term pump operation over a period of months. During operation, the vertical shaft grease seal and also the helium barrier seal failed, requiring beam shut down and repairs.

2. Inadequate vendor monitoring of design changes in the moderator led to a problem with one short supply tube and a moderator that could not operate at power. This was later repaired in place.

3. Deflections within the inner reflector plug during handling were not adequately evaluated and the initial on-site lift may have contributed to transfer line leaks requiring removal and repair.

4. Not enough design work was done to develop leak check methods for the target mercury loop after a target change. When one target did not pass the leak check after installation, there was an intense effort to develop methods in a full remote-handling environment, which was difficult.

5. The 7.5 kW moderator refrigerator had numerous problems and caused a loss of reliability during the first few years. Installation of an instrument in the warm leg to the cold box detected hydrocarbons coming from the compressor system and led to a final fix of the system. Such instrumentation should be part of the initial design and refrigerator procurement should be closely monitored. Early on-site testing is needed.

6. The accumulators in the moderator loops may be damaged or may leak, and should therefore be designed to be accessible. Both SNS and J-PARC have had to replace an accumulator.

MEGAPIE target

Experience with the MEGAPIE target provides information concerning the design, construction, operation and dismantling of a liquid metal target operating at the 1 MW level [616].

1. In general, simplification of the target design is desirable, for instance the use of only one electromagnetic pump, instead of two as were used in MEGAPIE.

2. For the heat removal system, it is desirable to avoid oil as a medium for an intermediate cooling loop, and the corresponding fire safety equipment. Possible alternative solutions could be direct water-cooling of LBE or an intermediate liquid metal loop.

3. Information stemming from the analysis of the operation of the gas systems includes: light gases are the greatest contributors to pressure build-up in the target cover gas system. In the experiment, one of the pressure transducers failed during operation, demonstrating the importance of having more measuring devices for a reliable measuring system. Moreover, leaks of radioactive xenon isotopes produced in the LBE were detected in the insulation gas system, corresponding to roughly 1% of the amount of the total inventory in the cover gas system. The issue of leaks between target components should be taken into account in the target design.

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