PROGRESS ON THE ESS PROJECT CONSTRUCTION

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Abstract

The construction of the European Spallation Source (ESS) is advancing at a high pace with the support of many laboratories and institutions all over Europe. Prototyping and manufacturing for the accelerator are in full swing in more than 23 laboratories distributed over 12 European partner countries. The origin and goals of the ESS will be briefly outlined in this paper. The milestones achieved, both in Lund and at the partner labs will be described as well as the plans up to operations.

DESCRIPTION

History

The ESS [1] is the materialization of a long-standing request of the community of neutron physicists in Europe. Following the selection of the green-field site of Lund (Sweden) in 2009, the host countries, Sweden and Denmark, invested resources recruiting specialists worldwide to update the design and refine the planning. Construction formally started in 2013, with the goal of being in operation in 2025 with a set of 16 instruments.

The European Spallation Source was set-up as a European Research Infrastructure Consortium (ERIC) by decision of the European Commission in August 2015 [2].

ESS facility

The ESS [3] consists of a ~500 m long 2 GeV superconducting proton linac [4, 5] sending beam on a tungsten target with moderators from which beam lines guide neutrons to instruments (see site layout in Fig. 1). It differs from most existing or planned neutron spallation sources by being a long pulse source with significantly higher performance, with a record beam power of 5 MW, a high number of beam ports (42) and a novel type of moderator providing much brighter neutrons beams. The main parameters are summarized in Table 1. Availability is another important requirement with the ultimate goal of 95 %.

Table 1: ESS Main Characteristics

Parameter	**Value**	**Unit**
Average proton beam power	5	MW
Proton kinetic energy	2	GeV
Pulse repetition rate	14	Hz
Pulse length	2.86	ms
Average current during pulse	65	mA
Number of moderators	2	
Number of neutron beam ports	42	

Specificities

State-of-the-art technology from European institutes and industry in the partner countries is key to reaching the required performances in a green-field site (Table 2).

Table 2: In-kind Partners to the ESS Machine

Institute (Country)	**Work packages**	**ESS subproj.**
CEA Saclay (FR)	RFQ, Cryomodules assembly, Beam Instrumentation, Controls…	Accel., ICS
CNRS Orsay (FR)	Spoke cav. & cryomodules, cryo. distrib. + Controls	Accel., ICS
ESS-Bilbao (ES)	Modulators (NC + Medium β linac), RF NC linac, MEBT + Controls, Target wheel + shaft + drive, Monolith vessel, Proton beam window, Beam dump	Accel., ICS, Target
INFN /Legnaro/ Catania /Milano + Elettra + CNR (IT)	Ion source + LEBT, DTL + controls, Medium β cavities, Magnets + power converters, RF amplifiers (Spokes), Irradiation module	Accel., ICS, Target
STFC Daresbury + Huddersfield (UK)	High β cavities, RF distribution, vacuum equipment,	Accel.
UKAEA (UK)	Active cell equipment	Target
IFJ-PAN, TU-Lodz, WUT (PL)	Installation power converters + RF + cryo. distrib. + exp. test place + LLRF fab.+ γ blockers	Accel.
Uppsala Uni., Lund Uni. (SE)	Spoke testing, Target Beam Instr., LLRF dev., Mod. dev., high power RF tests, controls	Accel., Target, ICS
Oslo Uni., IFE (NO)	Beam Instr., MCR design + eqt., software, …	Accel., ICS
Tallin Tech. Uni. (EE)	Controls eqt.	ICS
PSI, ZHAW (CH)	Controls eqt.	ICS
ATOMKI (HU)	RF protection system	Accel.
Aarhus Uni., DTU (DK)	Beam delivery system, Beam Instr., W release factors meas.	Accel., Target
UJF (CZ)	Target He cooling system, water cooling, Target HVAC	Target
FZJ (DE)	Moderator/reflector, LH2 cryoplant, Cryo. moderator	Target

This is achieved with in-kind contributions representing approximately 2/3 of the cost of construction, excluding Conventional Facilities which are supported by the host countries.

Sustainability is a key objective which has been pursued from the design phase, with the systematic search for solutions minimizing electrical consumption and the plan for efficiently transferring heat into the district heating system.

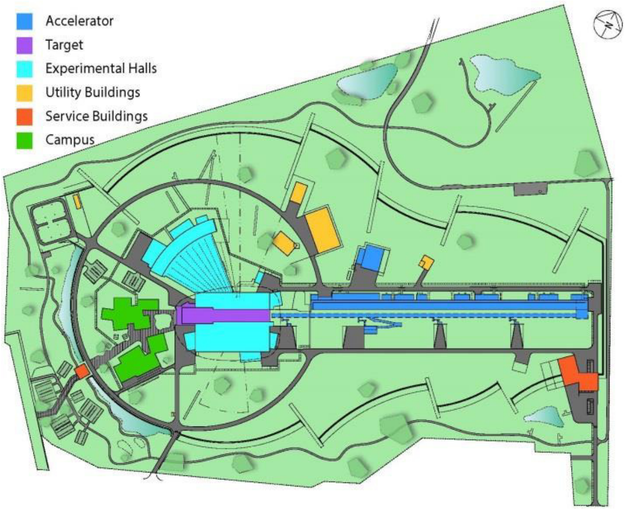

Figure 1: Site layout.

LINAC

Design

Collaboration with expert teams throughout Europe has been crucial to the optimization of the design of the accelerator (see block diagram in Fig. 2) [5]. The low energy part of the linac is using normal conducting accelerating structures (4 vane RFQ followed by five DTL tanks) to accelerate the protons from the ion source up to 90 MeV. Above this energy all accelerating structures are superconducting. Spoke cavities are used up to 216 MeV, followed by 6 cell elliptical cavities up to 571 MeV and finally 5 cell elliptical cavities (see Table 3).

The RF systems driving these accelerating structures have to provide a peak power of 125 MW to the beam during the beam pulse. Efficiency shall therefore be maximized to reduce electrical consumption and the unavoidably generated heat is worth recovering. For these purposes, prototypes Multi-Beam IOTs (MB-IOT) have been ordered from industry, a new type of high efficiency modulator has been developed and high temperature cooling of RF loads and klystron collectors is foreseen.

The different types of RF power amplifiers along the linac are listed in Table 4.

Table 3: Accelerating Structures

Type	**Optim. β**	**Freq. (MHz)**	**Gradient (MV/m)**	**No. of cav. (CMs)**
RFQ		352.2		1
DTL		352.2		5
Spoke	0.5	352.2	9	26 (13)
Medium β elliptical	0.67	704.4	16.7	36 (9)
High β elliptical	0.86	704.4	20	84 (21)

Status

Ion Source and LEBT The Microwave Discharge Ion source is being developed by INFN in Catania (Italy). Quasi- nominal performance has already been obtained in Catania where optimization is being pursued [6]. It will be shipped to Lund and installed in the accelerator tunnel before the end of 2017.

RFQ The 3.6 MeV four vane RFQ will be provided by CEA-Saclay (France) [7]. Fabrication is in progress. In July 2018 all modules will start being delivered at Lund and installed in the tunnel where the whole structure will be finely retuned and RF conditioned. Acceptance is planned in November 2018.

MEBT ESS-Bilbao (Spain) is taking care of the MEBT [8, 9]. Prototyping of components is well advanced.

Table 4: RF Systems

Type of accel. structure	**No.**	**Freq. (MHz)**	**Type of Amplifier**	**Peak power (MW)**
RFQ	1	352.2	Klystron	1600
Bunchers	3	352.2	Solid-state	20
DTL	5	352.2	Klystron	2200
Spoke	26	352.2	Tetrode	330
Medium β elliptical	36	704.4	Klystron	870
High β elliptical	84	704.4	MB-IOT or Klystron	1100

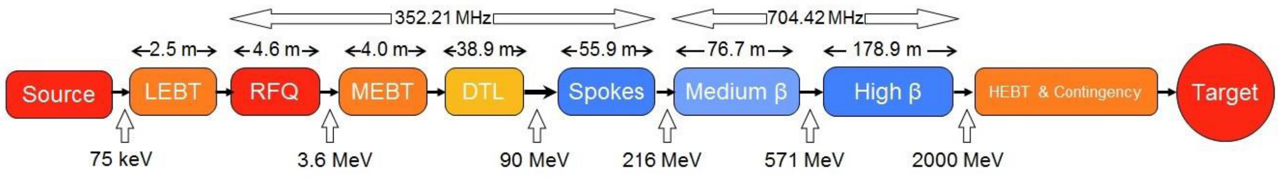

Figure 2: ESS linac block diagram.

DTL The design and fabrication of the 5 tank DTL is the responsibility of INFN in Legnaro (Italy) [10]. To save time and simplify alignment, tanks will be assembled at Lund. The first tank assembly will start before the end of 2018.

Spoke linac The Double Spoke cavities which will be used between 90 and 216 Me are first of their kind. The CNRS-Orsay (France) is responsible for the design and fabrication of cavities and cryomodules [11, 12], and also of the cryodistribution line. The three prototypes cavities have comfortably exceeded the ESS requirements (Fig. 3). A prototype cryomodule is being assembled and will be tested during the summer 2017 at full RF power in the FREIA facility in Uppsala [13, 14]. The first of the 13 cryomodules to be installed in the linac will arrive at Lund one year later, after having been tested in Uppsala.

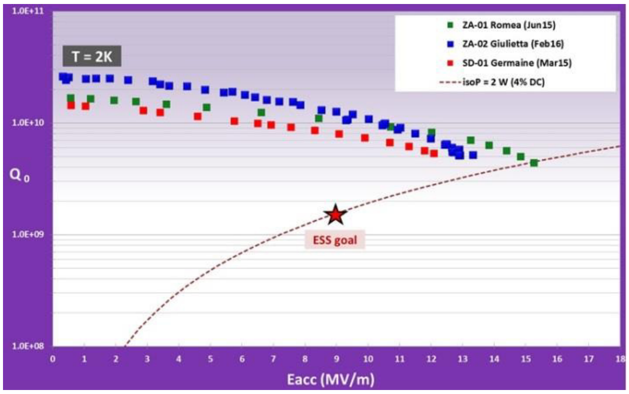

Figure 3: Q(E_{acc}) of the 3 Spoke CNRS prototypes.

Elliptical cavities linac Design and prototyping of the elliptical cavities and their cryomodules were initially handled by the CEA in Saclay [11, 15] and cavity prototypes demonstrated adequate performance. For series production, however, INFN-Milano will take care of the Medium β cavities, STFC-Daresbury (UK) of the High β and CEA-Saclay will assemble the thirty 6.6 meter long cryomodules (Fig. 4). Medium β cavities have 6 cells and almost the same length than the 5 cells High β cavities, which allows using similar cryomodules.

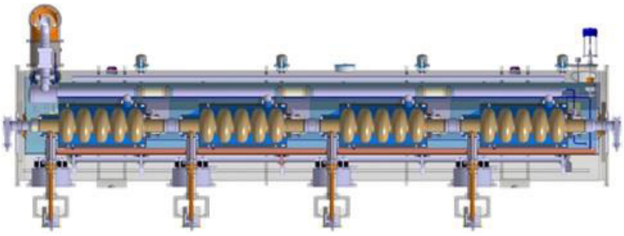

Figure 4: Cut view of High β elliptical cryomodule.

The first prototype cavity from INFN-Milano has already largely exceeded the ESS requirements (Fig. 5) [16]. Elliptical cryomodules will be tested in a dedicated test place located at the high energy end of the klystron gallery [14] before being installed in the tunnel. The first Medium β cryomodule will be delivered at Lund before the end of 2018 and all will be installed before the end of 2019. Installation of High β cryomodules will follow after March 2020.

RF The high power RF systems (Table 4) are at the procurement phase. The only pending decision concerns the amplifiers of the High β section which will depend on the outcome of the on-going tests of MB-IOT prototypes at CERN. Promising performance has already been measured during the factory acceptance tests of the device built by L3 (Fig. 6) which showed an efficiency consistently exceeding 60 % over the power output range from 0.6 to 1.2 MW [17]. A klystron has also been tested and demonstrated a noticeably improved efficiency at reduced output power, using an iris in the waveguide [17]. High power RF distribution with couplers, isolators, loads etc. will by delivered by STFC-Huddersfield [18].

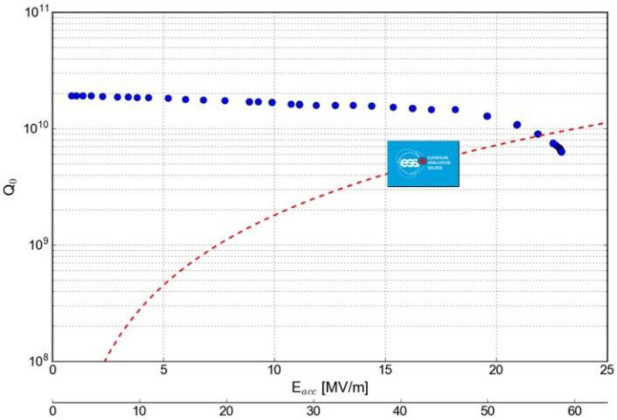

Figure 5: Q(E_{acc}) of Medium β cavity INFN prototype.

The high power modulators supplying the klystrons have to meet tight requirements regarding efficiency, disturbance of the network and reliability. It has been the subject of a successful in-house development at Lund based on the Stack Multi-Level Topology (SML) (Fig. 7) [19]. Low Level RF has been developed in close collaboration with Lund University, based on an MTCA.4 platform. Production will handled by in-kind partners in Poland and Spain [20, 21].

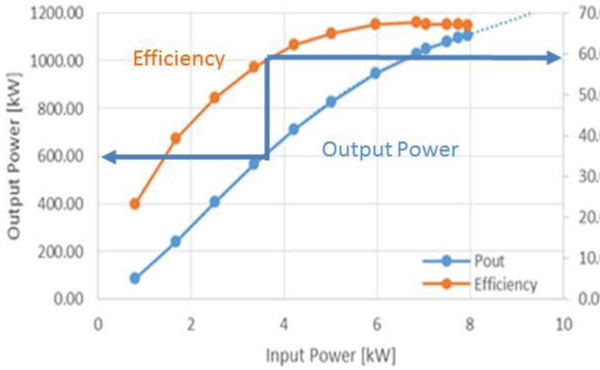

Figure 6: Efficiency of MB-IOT (L3).

Other systems A large size cryogenic system will be necessary to fulfil the needs of accelerator, target moderator, test place and instruments. The first of the 3 cryoplants will be delivered this summer. The cryodistribution lines for the Spoke section will be installed by the CNRS-Orsay and the line for the Elliptical section by Polish collaborators before Spring 2019.

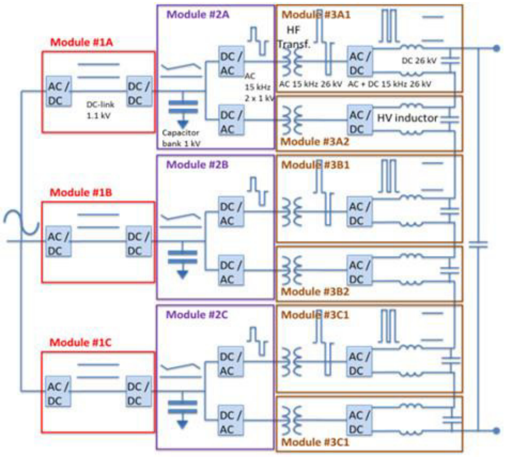

Figure 7: Schematics of SML Modulator.

Aarhus University (DK) is responsible for the beam delivery system which will raster scan the beam and minimize the peak current on target.

Lattice magnets have been designed and are being procured by Elettra (Italy) which also take care of the power converters [22].

STFC-Daresbury is in charge of most vacuum equipment and delivery of test systems and prototypes has already been made.

Multiple partners will contribute to the extensive inventory of beam instrumentation.

Planning

The accelerator buildings are progressively being made accessible and available for installation of additional infrastructure (Pipes, cable trays and cables etc.). The ion source will deliver its first beam at 75 keV at the beginning of 2018. Accelerating structures and other beam line components will then be progressively installed and commissioned until the end of 2019 when beam energy will reach 570 MeV [23]. The plan afterwards is to alternate beam commissioning on the Tuning Beam Dump and installation of High β cryomodules so that the energy of the first beam sent to the Target in October 2020 should be significantly higher than 570 MeV. Physics with instruments will then begin simultaneously with further commissioning of the linac and installation of the remaining High β cryomodules will have to take place during physics shutdown.

TARGET STATION

Description

The Target station building hosts the 6 m high, 11 m diameter target monolith (see Fig. 8) and all the services and systems necessary for the operation of target and moderators [3, 24]. The target itself is made of tungsten bricks arranged in 36 sectors inside a stainless steel pressure vessel in the shape of a 2.6 m diameter wheel [25]. Its speed of rotation is such that proton pulses hit successively neighboring sectors. As the beam repetition rate is 14 Hz, the wheel rotates at 14/36 = 0.39 rev/s. The proton beam is raster-scanned during each 2.86 ms burst to limit the peak current density on target to 53 μA/cm^2. Circulating helium gas pressurized to 11 bar will be used to cool the target and evacuate ~3 MW of heat.

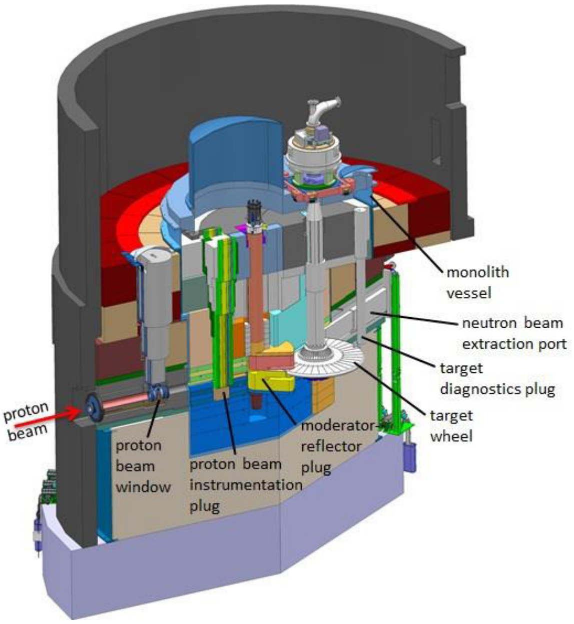

Figure 8: Cut view of target monolith.

Moderator/reflector systems, situated immediately above and below the beam impact location slow down the spallation neutrons, using ambient temperature water as well as cryogenic liquid hydrogen. Neutron beam line penetrations in the monolith couple the moderators to the neutron scattering instruments (Fig. 8), offering access to both thermal and cold neutrons. Innovative "double-decker" beam extraction ports allow any of the 42 beam lines to view either the upper or the lower moderator. Monolith components are encased in ~3000 tonnes of steel that acts as biological shield against the very harsh ionizing radiation that the spallation process produces.

Fluid cooling systems (helium and water), a cryoplant for moderator system refrigeration, an active cell facility and a 95 t capacity crane are the main support items filling the rest of the 130 m long target station building (Fig. 9).

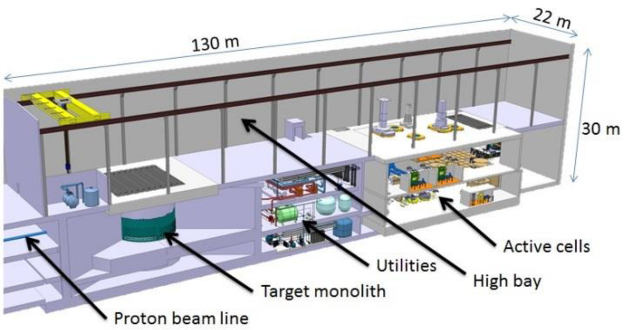

Figure 9: Cut view of target station building.

The Target team is also responsible for the Beam Dump which will be used for tuning the accelerator.

Status

The 2.6 m diameter target wheel with its shaft and drive unit are being designed and built by ESS Bilbao which is also in charge of the proton beam window and the monolith vessel. The detailed design of the wheel and shaft is completed and the fabrication of a prototype has begun in Spain. The Helium cooling system will be provided as an in-kind by UJF in Czech Republic. Helium circulators have been ordered. Moderators/ Reflectors and associated cryogenic hydrogen system will be delivered as an in-kind by FZJ (Germany). Following successful design reviews, procurement and fabrication are in progress.

Concrete shielding blocks for the Tuning Beam Dump were the first in-kind contribution delivered and installed on site at the end of 2016. Installation of more systems will follow during 2017, in parallel with civil construction. The most intense site works period will be 2018 when the major part of the in-kind deliveries will arrive.

According to the project schedule, all necessary equipment will be delivered and installed and the Target will be ready for beam in March 2020. The plan however is to send beam on Target only in October 2020, and to use the period March-October to practice installation and removal of target and moderators from the monolith on non-activated components.

INSTRUMENTS

The first 15 public neutron instruments that will be operational at the end of the construction phase (2025) are defined and in-kind partners have been selected. They are located in experimental halls at different distances from the target, depending on their specific needs (see Fig. 10).

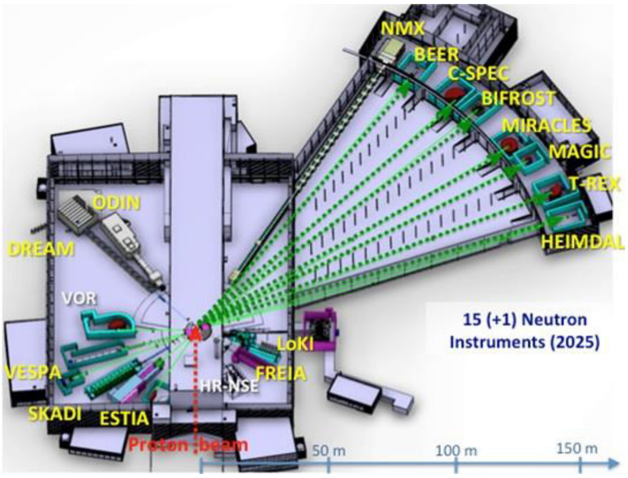

Figure 10: ESS first 15 instruments.

Commissioning of the first instruments will begin in February 2021. The user programme is scheduled to start in August 2023 with more than 8 instruments operational. At the end of construction, in December 2025, 15 instruments will be in use and the next seven will be in construction or in an advanced stage of design.

CONTROLS

The Integrated Control System [26] will take care of the whole ESS facility, including accelerator, target, site infrastructure and controls of the instrument components. Integration of the instruments and experimental data storage are the responsibility of the Data Management and Software Center (DMSC), located in Copenhagen.

The control system is based on version 7 of the EPICS software toolbox. Timing and synchronization is using the latest generation of the event system developed by Micro-Research Finland [27, 28]. Pre-production hardware has been validated on the ion test stand in Catania.

The MTCA.4 standard will be used for systems like Low Level RF and Beam Instrumentation which operate in real-time with fast signal acquisition and short latencies. A modular, digital hardware platform is being developed, based on experience from Paul Scherrer Institute which will allow for re-use of earlier soft- and firmware development. A pre-series of cards has been successfully tested and the first production batch has been initiated. For systems with less demanding data rates, the EtherCAT standard will be used. For process control applications, like control of vacuum and cryogenics equipment, standard industrial PLCs will be deployed.

The Configuration Controls Configuration Database (CCDB) which will store data about control system components and their hierarchies, plus several types of metadata is already operational.

For software development, a unified environment is provided that facilitates standardized software development and deliveries.

The Main Control Room which will be located on the Campus-facing side of the Target building (Fig. 1) will only be available when this building will be finished, in 2020. A temporary Control Room located at the high energy end of the klystron gallery will therefore be used initially. Installation has started with equipment delivered from the in-kind partner IFE (Norway).

PROTECTION SYSTEMS

The high beam power of ESS can cause huge damage in case of uncontrolled beam loss. An efficient and highly reliable Machine Protection System (MPS) [29, 30] will be implemented in order to prevent and mitigate damage to the machine, as well as prevent excessive beam-induced activation having the potential to produce long-term deterioration or increase maintenance times.

A modern Personnel Safety System (PSS) developed in accordance with IEC 61508 standard will control the access to zones with safety hazards [31], like e.g. accelerator tunnel or instruments.

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