THE ESS ACCELERATOR

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Abstract

The European Spallation Source, ESS, is now in construction in Lund, Sweden. It will be a long-pulse spallation source, using a 2 GeV superconducting proton linac to deliver a 5 MW beam onto a rotating, helium-gas-cooled tungsten target. ESS is a partnership between, at present, 11 European nations. According to current planning, the accelerator will be ready for beam in 2019, and by 2023 ESS will start operating as a user facility. This paper reviews the current status of the accelerator project.

INTRODUCTION

Construction work at the ESS site started in the summer of 2014, and now, two years later, the accelerator tunnel is cast, the front-end building, klystron gallery and cold-box building are nearing completion, and piling for the target building is in progress. Work on instrument halls and laboratory and office buildings has begun or will begin in the near future.

At the same time, accelerator, target and neutron-instrument hardware is being designed, prototyped and built at the more than 100 partner institutions around Europe that will deliver in-kind contributions to ESS.

One of the top-level parameters of the ESS project [1] is the 5 MW average beam power. This will be achieved with a 62.5 mA peak beam current at 2 GeV energy, a 14 Hz pulse-repetition rate and a 2.86 ms pulse length.

This beam will hit a spallation target made from tungsten. It is a wheel with 36 sectors, rotating so that consecutive beam pulses will hit adjacent sectors. The wheel is cooled by gaseous helium.

The design of moderators and reflectors is essential for the performance of the neutron source. This design has gone through successive generations. An optimized configuration together with the long-pulse concept gives an unprecedented neutron brightness, and ESS will in total be up to 100 times more powerful than existing neutron sources.

There will be 16 neutron instruments built within the 1,843 M€ construction budget of ESS (plus another 90 M€ from the Swedish government for infrastructure), and another six instruments are included in the complete facility.

Before all instruments are built, however, ESS is expected to start operating as a user facility in 2023.

IN-KIND

A major fraction of the linac hardware is provided as in-kind contributions from accelerator laboratories across Europe or in collaboration with institutions in the host countries Sweden and Denmark that have agreed to provide all their funding as cash. Exceptions are mainly expensive, purely commercial equipment such as cryo plants and RF sources, where there is little academic interest for a potential in-kind partner but a substantial economic risk.

In this in-kind model, ESS in Lund is responsible for the overall design of the accelerator, largely expressed as requirement documents in several levels down to individual work packages. Detailed design, prototyping and manufacturing are then made at the partner laboratories, while ESS in Lund monitors progress through earned-value management and runs regular reviews of work packages and work units. When components arrive to the site, also a substantial fraction of the installation work will be done by in-kind labour. Continuous knowledge transfer during the course of the project is evidently important, since ESS will eventually take full ownership and responsibility of the facility.

Currently, work on the accelerator is under way at 23 partner institutions in 10 countries. The value of this work represents a little above 50% of the 510 M€ accelerator construction budget.

In-kind partners and their main contributions are: Aarhus University: Beam delivery system; Atomki, Debrecen: RF local protection system; University of Bergen: Ion source expertise; CEA Saclay: RFQ, elliptical cavities, cryomodules, beam diagnostics; Cockcroft Institute, Daresbury: Target imaging; DESY, Hamburg: Beam diagnostics; Elettra, Trieste: Spoke RF power, beam diagnostics, magnets, magnet power converters; ESS-Bilbao: MEBT, warm-linac RF, beam diagnostics; University of Huddersfield: RF distribution; IFJ PAN, Krakow: Manpower for installation and tests; INFN Catania: Ion source, LEBT; INFN Legnaro: DTL; INFN Milan: Medium-beta cavities; IPN Orsay: Spoke cavities, cryomodules, cryo distribution; Lodz University of Technology: LLRF; Lund University: LLRF, test stand; NCBJ, Swierk: LLRF, gamma blockers; University of Oslo: Beam diagnostics; STFC Daresbury Laboratory: High-beta cavities, vacuum; Tallinn University of Technology: Power converters; Uppsala University: Test stand; Warsaw University of Technology: LLRF, phase reference line; Wroclaw University of Technology: Cryo distribution.

Since no institution has expressed interest in either the accelerator cryo plant or the test stand and instruments cryo plant, the project schedule has forced ESS in Lund to procure these. (The cryo plant cooling the moderators will however be an in-kind contribution to the target.)

Also, there are no partners for klystrons, IOTs or the modulator production yet. Prototypes have been procured or built by ESS, but the series production is still open for in-kind contributions.

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LINAC

If the design goals for a spallation-source linac should be stated in only one sentence, it may be to produce the highest possible beam power at the lowest possible cost. The most important additional requirements for the ESS linac are that the machine has to operate safely and reliably, such that users as little as possible will have to return back home without data because the accelerator had a problem, and it is also required that beam losses are small, in order to minimize radiation doses to the staff and to allow hands-on maintenance of the accelerator components.

Physics puts additional constraints on the design, and basic beam-physics rules-of-thumb tell that the betatron phase advance in each of the three planes has to be less than 90 degrees, that the average phase advance has to change smoothly throughout the linac, and that the tune depression should be greater than 0.4.

Also technological limitations have to be taken into account. Among those are limits to acceleration gradients and power couplers. For example, the maximum electric surface field in the elliptical cavities is set to 45 MV/m, and the maximum instantaneous power to the beam per coupler in these cavities is 1.1 MW.

Given the relatively low duty factor of 4%, room-temperature acceleration structures are economical at low energy. At ESS, they are used up to an energy of 90 MeV. Acceleration to 75 keV is achieved from the ion-source platform, up to 3.6 MeV in an RFQ, and then by five DTL tanks up to 90 MeV. Superconducting structures at 2 K then take over. Double-spoke cavities are used up to 216 MeV, medium-beta ($\beta = 0.67$) elliptical cavities take the beam to 571 MeV and high-beta ($\beta = 0.86$) elliptical cavities to the full energy of 2 GeV. The RF frequency is 352.21 MHz up through the spoke section, and then it doubles to 704.42 MHz in the elliptical cavities.

An optimization [2] with respect to criteria like the ones just mentioned results in a power to the beam per cavity as in Fig 1.

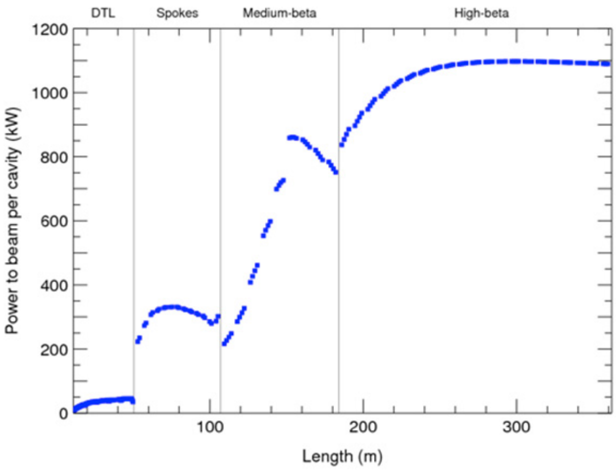

Figure 1: Power to the beam per cavity from the DTL through the superconducting linac.

One of the outputs of the optimization and this energy-gain curve is the length of the accelerator, which both through real-estate and a component count is closely related to the construction cost.

RF DEVELOPMENTS

The majority of the power delivered to the beam comes from the high power amplifiers in the 704 MHz parts of the linac. The medium-beta linac will have 36 klystrons capable of delivering up to 1.5 MW at saturation. ESS has placed three contracts for prototypes from three different vendors. Due to the spread in power requirements in the medium-beta part of the linac, the klystrons have been optimized to allow them to be operated at reduced voltage, and in addition each klystron is being tested with a variable mismatch in the output line. The first klystron has already been tested and delivered to ESS and demonstrated an efficiency of $> 65\%$ at saturation at 600 kW and at 1.5 MW.

The high-beta linac will have 84 RF sources. ESS are working with industry to deliver two technology demonstrators of multibeam (MB) IOTs, each capable of delivering 1.2 MW during the flat top pulse. The key advantage of the MB-IOT is that it maintains high efficiency over a broad output power range at the point of operation, critical to enable ESS to meet its stringent energy targets. Both MB-IOT designs are complete, and each contains 10 individual beams combined in a single toroidal output cavity. The first IOT by L3 Communications Electron Devices, shown in Fig 2, is under test in the factory and has already demonstrated high efficiency and 1.2 MW RF output power. The second IOT being manufactured by a consortium of Thales Electron Devices (TED) and Communications & Power Industries (CPI) will start testing in November 2016.

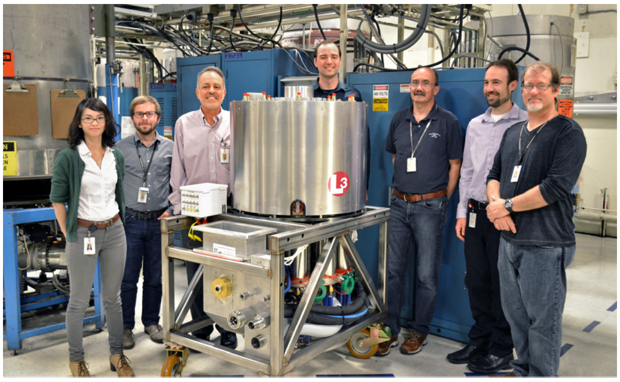

Figure 2: L-3 Communications Electron Devices' L6200 1.2 MW, 704 MHz multi-beam IOT for ESS.

OTHER RECENT DEVELOPMENTS

Development work has started on all the accelerator components that will be delivered as in-kind contributions. For the partners that joined the ESS project already in the design phase, this is true since a long time. Other partners joined more recently during the construction phase, but also here progress is rapid. There are additional development activities taking place in Lund on modulators and LLRF. In total 30 PDRs (Preliminary Design Reviews) and CDRs (Critical Design Reviews) of accelerator systems or sub-systems have taken place in Lund or at partner laboratories during the last 12 months.

Many systems, especially complex ones with long lead times, have moved from design to prototyping, and in some cases even production. In Catania, the construction of the proton source [3], see Fig 3, recently had reached the point where the first plasma could be observed. The proton source will be the first piece of the linac to be delivered to Lund, and arrival is planned for the late autumn of 2017.

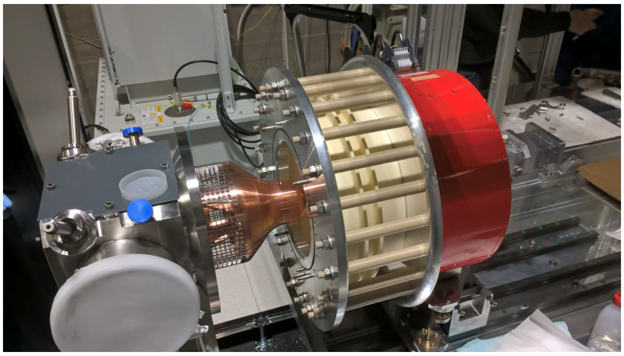

Figure 3: The microwave-discharge ion source designed and built by INFN in Catania.

Prototype spoke cavities [4] have been delivered to Orsay and tested since spring 2015. They have exceeded the ESS requirements of a gradient of 9 MV/m at a Q_0 of 1×10^9 with a good margin. A prototype spoke cryomodule is now being built up at Orsay.

Similarly, the first high-beta elliptical cavity prototype was delivered to Saclay already in 2014 and the first medium-beta cavity prototype was delivered at the end of 2015 [5]. Also these have exceeded the ESS requirements in vertical tests. Components of the first cryomodule, the Medium-beta Elliptical Cavity Cryomodule Demonstrator (M-ECCTD) are being assembled with the goal to start testing it in early 2017. The series cavities will be procured and tested by LASA for the medium betas and by Daresbury Laboratory for the high betas, and they will then be delivered to Saclay for assembly into cryomodules.

Further examples of existing prototypes include a MEBT buncher cavity in Bilbao, a LLRF system at Lund University, DTL permanent-magnet quadrupoles in Legnaro as well as an electro-magnetic quadrupole for the elliptical linac at Elettra. Furthermore, a non-ESS superconducting cavity has been successfully tested at the 352 MHz test stand at Uppsala University.

OUTLOOK

While linac components are being built at the partner laboratories, planning at ESS in Lund is now to a large extent focusing on the installation phase. Detailed installation plans have been worked out for the accelerator tunnel, for the klystron gallery which contains many more components than the tunnel, and for the stubs connecting the two.

Installation in the stubs will be a particularly challenging task. They will contain both waveguides and cables. They will have to be provided with cooling because of the power dissipation in waveguides and cables. And they must prevent neutron radiation from leaking from the tunnel into the gallery while still being, albeit with some effort, serviceable.

According to the current plans, full access to the accelerator tunnel will be given in March 2017, and the accelerator should be ready to produce a 571 MeV beam by June 2019 (the high-beta installation will continue until 2022). During this time, for instance around 600 km of cables need to be pulled and connectors need to be clamped to them, and more than 300 racks need to be filled with electronics up through the medium betas. This means that many teams will have to work in parallel with both installation and testing activities, and at the same time commissioning of parts of the accelerator will take place.

ACKNOWLEDGEMENT

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