

**Project Specification to Contract Agreement for**

**Accelerator Design Update  
and  
704 MHz RF Test Facility**

**for the European Spallation Source at Uppsala University**

# 1. ESS Accelerator RF Systems

## 1.1. Introduction

The European Spallation Source (ESS) is a pulsed spallation source producing neutrons for scientific research. The Swedish Government and its international partners have decided that ESS will be constructed in Lund close to the foreseen site for the future MAX IV synchrotron radiation laboratory. ESS consists of a proton linear accelerator, a target station and neutron beam lines for user's experiments. The neutrons are extracted in a fission process from their bound states in heavy atomic nuclei of the target. The energy required for the fission process is created by bombarding the nuclei with high energy protons from the proton linear accelerator. The projected time line is to have a Technical Design Report (TDR) by 2012, to start installation on-site four years later and to have the first beam by 2019.

ESS has initiated an Accelerator Design Update project (ADU) to prepare the TDR including cost estimation for the accelerator construction. The starting point of the ADU is a conceptual design described in the 2010 publication "Conceptual Design of the ESS Linac", TU6PFP083 of the International Particle Accelerator Conference IPAC'10 proceedings. This design, in turn, is based on the "The ESS Project" report from 2003, excluding the proposed short pulse target station. The Radio Frequency (RF) Systems Work Package number 8 (WP8) of the ADU addresses the design and development of the RF power generation, control and distribution for the ESS proton linac. Specific for the ESS proton linac, in relation to other proton linacs, is the high power level required. The radio frequency (RF) system, that has to generate this power and distribute it to the accelerating cavities, is a main resource driver for linear accelerators in terms of investment, operation and maintenance resources such as material, electricity and manpower. Therefore the focus is on R&D that will decrease investment, operation and maintenance resources required for the RF system without compromising its reliability. R&D to improve the overall energy efficiency has the main priority.

The RF system connects a total of 196 accelerating cavities. It is split in a 352 MHz part, consisting of 1 RF quadrupole (RFQ), 3 drift tube linac tanks (DTL) and 56 superconducting spoke cavities, and a 704 MHz part consisting of 136 superconducting elliptical cavities. The RF system of the ion source is developed in the ADU WP6 "Front End and Normal Conducting Linac" (and therefore not part of WP8 "RF Systems"). The baseline concept for both 352 and 704 MHz parts is a point-to-point generation and distribution of the RF power from a single source to a single accelerating cavity. This is a well established but conservative technology that is available 'off the shelf'. However, as the cost of a RF power source with a certain power capacity is significantly lower than the cost of two RF power sources, each with half of the power capacity, there can be a major savings in resources by driving multiple cavities with a single RF power source. Also, different technologies like a combination of a large number of small solid state RF power amplifiers might in some cases be a more resource effective and reliable alternative than a single large klystron-type power amplifier. Furthermore, the high power usage of the RF system requires a large amount of air and water cooling. Where possible, the design shall assure efficient heat recovery compatible with the ESS requirements for a "green" and energy efficient facility. The R&D in WP8 therefore shall determine the optimum configuration and technology for a resource effective and reliable power generation and distribution scheme. The resources required for maintenance and end-of-lifetime replacement shall be included in the study.

The 704 MHz part of the ESS linac consists of 40 low- $\beta$  cavities and 96 high- $\beta$  cavities. The high- $\beta$  superconducting elliptical cavities have the highest power requirements at 1.2 MW per pulse, and subsequently offer the largest prospects for resource savings. A resource saving option with respect to the point-to-point baseline concept is to power two (or more) of these cavities with a single RF power source. This will require an intermediate high power amplitude attenuator and phase shifter, a so-called vector modulator, to enable individual control of the RF power to each cavity. The development of a resource efficient RF system, including associated power generation and distribution systems, and test in a two-cavities-per-klystron concept with a low loss vector modulator, is a priority task for ESS. A test facility has to be constructed with a complete 704 MHz RF system; for test of the cavities, for test of the two-cavities-per-klystron concept and to test and optimize the RF system.

The 352 MHz part of the ESS linac consists of one RFQ, 3 DTL tanks and 56 superconducting spoke cavities at two different  $\beta$ 's. Both the RFQ and the DTL will be developed from existing designs already in operation. Superconducting spoke cavities have however not yet been used in a linac, thus extensive testing will be important. This implies that a test facility has to be constructed with a complete 352 MHz RF system; for test of the cavities but also to test and optimize the

RF system. As for the 704 MHz system, also here it is to be investigated what are the optimal and resource efficient solutions for the RF power generation and distribution systems.

## **1.2. The Accelerator Design Update Project**

To prepare for the bidding process and construction phase of the accelerator, the WP8 (RF Systems) of the ADU carries out an investigation to describe the parameters, design and cost estimate of the overall RF system. A Technical Design Report (TDR) has to be published for external review. The TDR shall describe the chosen concepts and technical description of the both the 352 and 704 MHz RF systems for the whole ESS proton linac and include a cost estimate. Alternative solutions shall be included for problems where the R&D has not yet been conclusive. The TDR should be ready at the end of 2012.

## **1.3. The 704 MHz RF Test Facility**

Reliable development of an energy efficient and resource effective RF system requires test of the individual components and the complete RF system in a realistic environment. Thus an RF test facility is required with which the different concepts, topologies and elements of the RF system can be investigated in an in-depth test program. The RF test facility requires a complete 704 MHz RF system consisting of the LLRF, RF power generation and RF power distribution systems as well as accelerating cavities. To test the two cavities per klystron concept requires two elliptical cavities installed in a horizontal cryostat. If possibly, both cavities should be installed in the same cryostat in order to investigate if any cross talk or coupling occurs between the two cavities. A 704 MHz RF Test Facility should be built up and used for the testing of the prototype 704 MHz RF system for the two cavities per klystron concept during an initial period 2011 – 2014.

After the initial period, during the industrial tendering and production of the ESS proton linac, the Test Facility could be used to test complete so-called cryomodules. A cryomodule is a cryostat containing up to eight superconducting elliptical cavities cooled to 2 K. 25 Cryomodules, extending 13 m each, are required to complete the ESS proton linac.

## **2. Uppsala University Participation in the ADU Project**

ESS has prepared a project specification for the overall ADU: “Project Specification for ESS Accelerator Design Update Project”, dated 2010-12-15 Rev.1.0. Uppsala University will participate in the WP8 (RF Systems). The WP8 related Work Unit (WU) numbers indicated in the text below are the same as those used in the ADU project specification.

Uppsala University will

- coordinate the ADU WP8 RF Systems.
- coordinate the ADU WU8.1, WU8.4, WU8.5.
- coordinate the ADU WP8 RF Systems TDR writing and cost estimation.
- participate in the mathematical model development of a two-cavities-per-klystron concept (WU8.2).
- participate in the LLRF development or a two-cavities-per-klystron concept (WU8.3).
- investigate alternative solutions for RF power generation and distribution (WU8.4 and WU8.5).

The sections below include the text relevant for the work by Uppsala University while none relevant Work Unit parts have been deleted from the text below.

### **2.1. Work Unit 8.1: Management and TDR**

- Coordination and scheduling of the WP tasks.
- Monitoring the ongoing work, informing the project management and the WP participants.
- WP budget follow-up.
- Coordinate the conceptual design, cost estimation and writing work for a technical design report on the ESS proton linac RF system.
- Prepare the technical specifications required for the tendering process following the technical design report.

The activities of this work unit (WU) are to oversee and co-ordinate the work of all the other WUs of the WP concerned, to ensure the consistency of the WP work according to the project plan and to coordinate the WP technical and scientific tasks with the tasks carried out by the other work packages when it is relevant. The coordination duties also include the organization of WP internal steering meetings, the setting up of proper reviewing, the reporting to the project management and the distribution of the information within the WP as well as to the other work packages running in parallel.

This WU coordinates the writing of the ESS proton linac technical design report (TDR) parts relevant to the activity of this WP. The TDR shall include the chosen concepts and technical design of the overall RF system for the whole ESS proton linac including a full cost (to completion) estimate with a precision better than 20%. Alternative solutions shall be included for problems where the R&D has not yet been conclusive. The TDR is to be completed by the end of 2012 and offer a safe baseline design from which it will be possible to prepare the technical specifications and detailed design of the overall RF system.

This WU also covers the organization of and support to dedicated to the WP activity review and possible activity workshops or specialized working sessions, implying the attendance of invited participants from inside and outside the WP.

**WU 8.1.1:** Coordination and monitoring of the WP8 activities. Information to and between project management and WP participants. Budget follow-up.

**WU 8.1.2:** Create a conceptual design of the overall RF system including an overview of all RF system components and their installation including a full cost (to completion) estimate. Write the TDR for the RF system as required for the different linac parts. The RF system design shall be interfaced to the design of WP4 (SCRF spoke cavities), WP5 (SCRF elliptical cavities) and WP6 (Front end and NC linac). Where possible, the design shall assure efficient heat recovery compatible with the requirements of the ESS infrastructure services. It shall investigate the requirements of the RF system based on existing installations and possible alternatives where equivalent solutions exist.

**WU 8.1.3:** Based on the TDR baseline, prepare a detailed design and the technical specifications required for the tendering process for the RF systems. Investigate which components can be ordered as standard objects from industry and which components require special design specifications.

## **2.2. Work Unit 8.2: RF Modelling**

- Participate in the development of mathematical models to describe the RF systems for the different accelerating cavity types and powering concepts.

To realize an optimal, energy efficient and low beam loss operation of the proton linac, a proper understanding of the RF system, including the interaction between accelerating cavities and proton beam, is required. Understanding the RF system behaviour and regulating it with the LLRF controls in turn requires an accurate mathematical model of the whole RF system including power distribution network behaviour, cavity response and beam interaction feedback. The model is then used to determine the RF system parameters and boundary conditions to which all parts in the system shall adhere. The modelling work includes higher order mode studies, damping schemes and inter-cavity transitions as well as RF simulations of a complete cryomodule with multiple cavities.

## **2.3. Work Unit 8.3: Low Level RF System**

- Participate in the development of a LLRF system for the 704 MHz two-cavities-per-klystron concept to be installed in the Uppsala Test Facility.

The low level RF (LLRF) system generates a low power level RF signal input for the RF power generation system. The LLRF system monitors the RF at the accelerating structure and uses this in a feedback loop to control amplitude and phase of the RF signal input. In addition the LLRF system adjusts the tuning of the accelerating cavity, if applicable, to ensure that the cavity resonance frequency matches the desired operation frequency. While the 704 MHz elliptical cavities have piezo tuners controlled by the LLRF, the 352 MHz RFQ and DTL are tuned by temperature control, regulated by their cooling water flow. Results from the RF modelling work unit will define if the frequency tuning is required.

## **2.4. Work Unit 8.4: RF Power Generation**

- Investigate alternative RF power generation technologies that are reliable, cost effective and energy efficient for long term operation and maintenance. The study shall include efficiency enhancement of klystrons, alternative power amplifiers like solid state devices and alternatives to operate them like powering multiple klystron power amplifiers from a single high voltage pulse modulator.

The RF power generation system amplifies the RF signal from the LLRF system to the power levels required to drive the accelerating cavities. For high power levels normally narrow-band klystron amplifiers are used. Such klystrons are powered by a high voltage power supply and pulse modulator. Klystrons are vacuum tubes with a thermo-cathode electron source, electron collector and in between an input resonance cavity, a drift tube and an output resonance cavity. Klystrons, high voltage power supplies and pulse modulators are commercially available, however not as off the shelf products at the required power levels. All are built according to proven but expensive technology and have a limited life time which requires frequent maintenance and replacement during the foreseen life time of ESS operation. Energy efficiency of commercial klystrons is presently below 66% and decreases in some cases with increasing power output. Cost effective, energy efficient and reliable alternatives for long term operation and maintenance shall be investigated.

## **2.5. Work Unit 8.5: RF Power Distribution**

- Investigate alternative RF power distribution schemes that are reliable, energy efficient and cost effective for long term operation and maintenance.

The RF power distribution system connects the power generation system with the accelerating cavity. The base line is to connect one accelerating cavity to one power generation system. However, to increase cost effectiveness, alternatives are to be investigated to connect multiple cavities to a single power generation system. This might require the inclusion of a vector modulator for individual regulation of the RF power amplitude and phase to each cavity. Such solution is however only viable if power losses in the distribution system can be minimized, as otherwise a loss of energy efficiency will cancel any other resource efficiency gains.

The power distribution system shall isolate the power generation system from any possible reflected power returning from the cavity. The design shall also include interfacing to the cavity's input power couplers which are part of either WP4 (SCRF spoke cavities) or WP5 (SCRF elliptical cavities).

### **3. Uppsala University 704 MHz RF Test Facility**

Uppsala University will build-up on its premises an RF test facility for the development of the ESS RF system. The technical description is detailed in the report: “The FREIA Helium Cooling and RF Test Facility”, Memo RR/2010/03 dated 2 June 2010, enclosed in the annex.

Uppsala University will

- construct and operate a facility for the development of the 704 MHz two-cavities-per-klystron concept.

#### **3.1. Description of the Test Facility**

The Uppsala Test Facility will be build-up in stages, starting with the 704 MHz RF power generation and distribution system, then a horizontal test stand that includes two superconducting elliptical cavities. In addition the facility needs to include electronic controls and auxiliary equipment as required to operate the facility.

The facility needs to be equipped with a 704 MHz klystron type microwave amplifier, a high voltage pulse modulator to drive the klystron, two superconducting 704 MHz elliptical cavities and a Low Level RF (LLRF) system.

The high power RF generation system consists of a high voltage pulse modulator and a klystron type microwave amplifier.

The high power RF distribution system connects the RF power generator to the accelerating cavities.

The LLRF system will be provided to Uppsala University by Lund University under agreement with ESS. The LLRF system generates the low power RF signal to be amplified in the klystron and adjusts the individual amplitude and phase to the two RF cavities by means of the intermediate fast vector modulators in the RF distribution system. The LLRF also measures the field in the cavities and tunes the cavity frequency to adjust for so-called Lorenz force detuning caused when the high power RF pulse starts filling the cavity volume.

The horizontal test stand consists of a cryostat with two superconducting elliptical cavities as used for the two-cavities-per-klystron concept development. In addition this requires that the test facility will be equipped with a helium refrigeration system to cool the cryostat and cavities.