2 Work Package and Work Unit descriptions

2.8 WP8: RF Systems (R. Ruber, Uppsala)

The RF systems work package (WP) 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 RF system, that has to generate this power and distribute it to the accelerating cavities, is a main resource driver for linear accelerators in form 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 and the LEBT buncher cavity. It is split in a 352 MHz part (LEBT buncher, 1 RFQ, 3 DTL and 56 spoke cavities) and a 704 MHz part (136 elliptical cavities). Note that the RF system of the ion source is included with the source as developed in WP6 (Front End and NC Linac). The baseline 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 relative cost of RF power sources decreases to a certain amount with increasing power output, there can be a major advantage in resources to drive multiple cavities with a single 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 this WP therefore shall determine the optimum configuration and technology to be used to develop 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.

Prototype RF systems and RF test facilities have to be developed for the 352 MHz spoke cavities, 704 MHz elliptical cavities and to test a two elliptical cavities per klystron concept. The prototype RF systems and the test facilities should be upgradable for future testing of complete cryomodules containing multiple cavities in a single cryostat.

The 704 MHz part of the ESS linac consists of 40 low-β cavities and 96 high-β cavities. The high-β 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 is to power two (or more) of these cavities with a single RF power source might 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 power amplifier concept with a low loss vector modulator, is therefore of priority for the R&D in this WP.

The 352 MHz part of the ESS linac consists of the LEBT buncher cavity, one RFQ, 3 DTL tanks and 56 superconducting spoke cavities at two different β's. Both RFQ and 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 immediately 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.

To prepare for the bidding process and construction phase, an investigation has to be carried out to describe the parameters, design and cost estimate of the overall RF system. A design report has to be published for external review. The design report shall include the chosen concepts and technical description of the overall RF system for the whole ESS proton linac including a cost estimate. Alternative solutions shall be included for problems where the R&D has not yet been conclusive. Based on this baseline a detailed technical design and specifications shall be prepared for the overall RF system.

Work Unit 8.1: Coordination and communication (R. Ruber, Uppsala)

- 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.

Work Unit 2: RF Modelling (RF Group Leader, EES)

- Prepare and maintain the list of nominal RF parameters.
- Develop mathematical models to describe the RF systems for the different accelerating cavity types and powering concepts.
- Develop RF simulation models to study the different types of accelerating cavities.

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.

The superconducting elliptical cavities, including corresponding input power couplers and higher order mode (HOM) output couplers used in the ESS linac have a high quality factor and correspondingly small bandwidth. These cavities are therefore extremely susceptible to mechanical perturbations either by ambient noise, temperature variations or Lorenz force detuning at each RF and beam pulse. The mathematical model will make it possible to understand and predict the behaviour of the RF system powering these cavities and determine the parameters and boundary conditions of the system.

- **WU 8.2.1:** Prepare and maintain the list of nominal RF parameters and boundary conditions. The list shall be based on the results of the RF modeling work in combination with input from the work packages that develop the accelerating cavities (WP4, WP5, WP6) and beam dynamics modeling (WP2).

- **WU 8.2.2:** Develop mathematical models to describe the RF system for the different accelerating cavity types and powering concepts with single or multiple cavities per power source. The models shall include RF-to-beam interaction and behavioural data from real cavities. Use the models to determine the parameters and boundary conditions to which the RF system shall adhere.

- **WU 8.2.3:** Develop RF simulation models of the accelerating cavities to study possibilities to increase the RF system efficiency, to study RF-to-beam interaction, higher order mode generation and damping schemes as well as inter-cavity transitions.

- **WU 8.2.4:** Study multipactor effects in the superconducting spoke and elliptical cavities and their power couplers. Were necessary and possible, optimize the design of the cavities and couplers to minimize the multipactor effects.

Work Unit 3: Low Level RF System (A. Johansson, Lund U)

- Investigate alternative LLRF system architectures.
- Design a LLRF system for the 352 MHz spoke cavities.
- Design a LLRF system for the 704 MHz elliptical cavities.
- Design a LLRF system for the 704 MHz two cavities per klystron concept.

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.

- **WU 8.3.1:** Investigate state of the art and alternative LLRF architectures, to decide on a suitable baseline design for the ESS proton linac. This includes investigation and simulation of possible optimizations of the LLRF control loops to reduce the beam loss in the linac, the need on including temperature control for the NC linac and microphonics and Lorenz detuning for the SC linac. Specifications should be done for the interfaces towards the global control system, and surrounding support systems such as beam diagnostics, machine timing, phase reference and interlocks.

- **WU 8.3.2:** Adopt baseline design for the LLRF control and monitor system for the 352 MHz NC linac.

- **WU 8.3.3:** Adopt baseline design for the LLRF control and monitor system for the 352 MHz superconducting spoke cavities.

- **WU 8.3.4:** Adopt baseline design for the LLRF control and monitor system for the 704 MHz superconducting elliptical cavities, including control of the cavity tuner.

- **WU 8.3.5:** Adopt baseline design for the LLRF control and monitor system for the option with two 704 MHz superconducting elliptical cavities connected in parallel to a single RF power generation source.

- **WU 8.3.6:** Development of (simple) klystron and cavity model for inclusion on LLRF hardware. The benefit of having a complete model of the klystron and cavity in the LLRF hardware is that it makes it possible to run the complete control system of the linac without a beam, and without spending power in the modulators and klystrons. If this can be done without adding undue cost and complexity to the LLRF-modules, it will facilitate commissioning, upkeep and upgrades of the control system of the linac.

- **WU 8.3.7:** Investigations of the feasibility of linearization of the Klystrons in the LLRF hardware. If it is possible to add linearization of the klystron to the design of the RF system, it will make it possible to run the klystron at a higher efficiency, and thus save energy. The system will be evaluated by calculation and initial simulations to decide if it is feasible. Results in form of estimated added complexity and cost to the LLRF platform will be included in the TDR. This work will be done in close cooperation with WU8.4 on RF power generation.

- **WU 8.3.8:** Global phase reference specification and design, including delivery system, for the LLRF-systems in collaboration with the WP2 control system. The performance of the LLRF system in form of phase noise and jitter is highly sensitive to the design of the local oscillator signals and the machine timing, including the distribution network. The final specifications on the LLRF system are dependent on this systems performance.

The LLRF systems will be installed and used in the test facilities. It might be possible to have a common baseline for the LLRF prototypes for 352 MHz and 704 MHz as well as for single or double cavity control. Differences will exist in signal (de)modulation and software.

Work Unit 4: RF Power Generation (A. Rydberg, Uppsala)

- Investigate alternative RF power generation technologies.

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.

- **WU 8.4.1:** Investigate alternative RF power generation systems 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.

Work Unit 5: RF Power Distribution (A. Rydberg, Uppsala)

- Investigate alternative RF power distribution schemes.

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).

- **WU 8.5.1:** Investigate alternative RF power distribution schemes that are reliable, energy efficient and cost effective for long term operation and maintenance.