

# **ESS Accelerator Design Update Work Packages**

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## 0 Project summary and objectives

Underlying accelerator technologies have evolved, and considerable experience has been gained, since the basic ESS design proposal was originally completed in 2002. Two multi-megawatt accelerator based spallation sources have been constructed: the SNS in the U.S. and J-PARC in Japan. New European and International accelerator projects are under construction, such as IFMIF/EVEDA, SPIRAL-2, and LINAC-4. Thus it is necessary to review and enhance the original ESS design, through the Accelerator Design Update (ADU) project.

The ADU operates within the pan-European ESS collaboration with the primary goal of producing a Technical Design Report for the accelerator, including full cost to completion, by the end of 2012. The ADU is building on the preliminary work already performed within the ESS-Bilbao and the ESS- Scandinavia initiatives, taking advantage of latest acquired knowledge and synergies with other on-going projects to make modifications that will improve the facility reliability, reduce costs and reduce project overall risks. The delivery of a consolidated TDR, complete with corresponding project planning, construction schedules and cost estimates, will enable the detail engineering and construction phase of ESS to be launched.

The ADU project consists of eight major Work Packages lead by different partner institutions. Each Work Package contains multiple Work Units, with leadership distributed among multiple participating institutions. Some Work Unit leaders are part of the Lund staff, enabling the team building effort that is necessary for future facility operation to begin.

The Work Package leaders are responsible for the following objectives:

1. Deliver a Technical Design Report (TDR) by the end of 2012.
2. Estimate the accelerator cost with a precision better than 20%, in most cases.
3. Provide a *readiness to construct*. That is, describe a safe baseline design with technical choices that will enable an immediate 2013 start on the generation of engineering design specifications, detailed drawings, and the construction of “late prototypes”.
4. Assure a *viable critical path* to commissioning and operation. That is, begin work on “early prototypes” that need to be completed before the end of 2012, and on other prototypes that must be started immediately, but which will not be completed by the end of 2012.
5. Work with the lead institution directorate to manage and monitor Work Package performance, if necessary resolving conflicts between partner institutions through the Collaboration Board, which has the ultimate responsibility for deliverables.
6. Take into account energy budgets and sustainability.

### 0.1 Work Package summaries

#### WP1: Management (M. Lindroos)

The development and construction of a project of the magnitude of the ESS requires the effort and collaboration of many countries, institutions, laboratories and companies all over the world. Due to this complexity, the implementation of a good organisation is critical. Therefore, it is necessary to remark that during the design update phase, high levels of project management, technological coordination, system engineering and quality assurance and configuration control will be needed to achieve a complete and coherent consolidated design in agreement with the specified needs. This Work Package will deal with all these project management related activities.

**WP2: Accelerator Science** (S. Peggs)

This Work Package includes Beam Physics, Control System, and Beam Instrumentation Work Units, identifying and performing analyses and simulations critical to determining a consistent set of parameters that are optimized for performance, reliability and feasibility. Work Package activities support the integration of accelerator design efforts in all Work Packages, and at all ESS collaborating partner institutions.

**WP3: Infrastructure and services** (J. Eguia)

The overall objective of this Work Package is to perform the design and specification of all infrastructure facilities and services, including HVAC (Heating, Ventilation & Air Conditioning), cryogenics system, supply of cooling water, electricity, and networking. ESS will be a climate-neutral and sustainable facility and this Work Package will work closely with the ESS energy team.

**WP4: Spoke superconducting linac** (S. Bousson)

This Work Package will address the engineering design of the complete spoke cryomodules which will compose the intermediate energy section of the ESS Superconducting Linac, based on multi-gap superconducting spoke resonators at 352 MHz.

The detailed design of the spoke cryomodule includes the cavity and the couplers. Early prototyping will be included in this work to validate part of the cavity and power couplers design and to justify the cavity design gradients. At the end of 2012, two spoke cavity prototypes and power couplers will be constructed and tested.

**WP5: Elliptical superconducting linac** (G. Devanz)

The main objective of this Work Package is to provide the engineering design of the fully equipped cryomodules for both medium and high beta elliptical cavity sections of the ESS linac operating at 2 K with an accelerating field of about 15 MV/m. The design should be carried out in close collaboration with the SPL development of a prototype cryomodule housing several high beta elliptical cavities. Several components, namely cavities, fundamental power couplers and fast frequency tuners are considered to be critical, therefore prototypes will be fabricated for each of them and tested.

**WP6: Normal conducting linac** (S. Gammino)

This Work Package will be responsible for the design of the elements of the front-end up to the warm-to-cold transition (proton source, beam transport system, radio frequency quadrupole and drift tube linacs). Different European laboratories contain the competences necessary to take the responsibility of the design, construction and integration of the whole NC part of the Linac. Existing equipment will provide a valuable test for the Ion Source. This test will be followed by a whole injector (source, low energy beam transport and RFQ) reliability test lasting about three months. The NC Linac design study would take advantage of this experiment and the experience of the design of similar linacs LINAC4, TRASCO and IPHI RFQ.

### **WP7: High Energy Beam Transport, NC magnets and Power Supplies** (S. Pape-Møller)

This Work package is concerned with the design of a HEBT system which functionalities include transport to the main target, to a commissioning beam dump, to an optional future target station, and a collimation section after the Linac. Also included in the scenario are considerations about bringing the HEBT into operation, i.e. a steering and a focusing concept. In addition to the above general design of the HEBT, this Work Package will also define standards for the normal conducting magnets, the corresponding power supplies, beam dumps and collimators for the whole Linac. Power supply studies addressing sustainability over a 10 year period are included.

### **WP8: Radio Frequency Systems** (R. Ruber)

This Work Package addresses the design and development of the RF power generation, its control and its distribution system for the ESS Linac. The RF system connects different accelerating structures and is split in a 352 MHz part (RFQ, DTL and spoke cavities) and a 704 MHz part (elliptical cavities). The activity in this Work Package will determine the optimum configuration and technology to be used to develop a resource effective, energy efficient and reliable power generation and distribution scheme. The resources required for maintenance and end-of-lifetime replacement will be included in the study.

## **0.2 Participating institutions**

Institutes participating in the ADU come from inside the European members states, and from countries all over the world. Institutes that are shown in **bold** in the following list host Work Package leaders:

- **Aarhus University (DN)**
- Argonne (USA)
- ASTEC (UK)
- BNL (USA)
- **CEA Saclay (FR)**
- CERN
- Ccroft Institute (UK)
- **CNRS Orsay (FR)**
- DESY (GE)
- ESS- Bilbao (ES)
- **INFN (IT)**
- JLab (USA)
- John Adams Institute (UK)
- Maribor Univ. (SI)
- Tech. Univ Darmstadt (GE)
- Technical University of Lisbon (PT)
- **Tekniker (ES)**
- TRIUMF (Canada)
- Oslo University (NO)
- Rostock Univ (GE)
- SNS (USA)
- Stockholm Univ (SE)

- Soltan Institute (PL)
- **Uppsala University (SE)**



Figure 1: Map of collaborating institutions in Europe. Labs leading Work Packages are marked with red stars. Other labs participating in the Work Packages are marked with orange rings.

# 1 Accelerator Design Update Work Packages

## 1.1 Management (M. Lindroos, ESS)

- 1) Coordinate the technical, scientific, financial and administrative activities of the collaboration with ultimate responsibility for cost control.
- 2) Integrate all ESS activities into a single coherent project.
- 3) Assure smooth transition between design and construction phase
- 3) Establish and maintain Linac parameter lists.

The development and construction of a project of the magnitude of the ESS requires the effort and collaboration of a lot of countries, institutions, laboratories and companies all over the EU and around the world. Due to this complexity, the implementation of a good organisation is critical. Therefore, it is necessary to remark that during the updating phase, high levels of project management, technological coordination, systems engineering and quality assurance and configuration control will be needed to achieve a complete and coherent consolidated design in agreement with the specified needs.

The proposed organization for this project is based on the development by means of in-kind contributions, organized in technology related tasks, of a large number of entities. This work organisation is suitable for this kind of projects, but for an optimal efficiency it is necessary to provide a technically strong and well resourced *Linac Management Team* with the ultimate responsibility and coordination control. For managing the collaboration and for purposes of coordination and control, two more bodies are foreseen: the *Linac Collaboration Board* and the *Linac Coordination Board*. A description of the roles of these three bodies is given in the “organisational structure and overall project management” section

The roles of the Linac Central Team are as follows:

### 1.1.1: System engineering (R. Duperrier, Saclay)

Requirements management and interface control. Verification of the appropriate integration of the Linac subsystems as a whole and check the coherence and compatibility of the components requirements. Technical validation and functional analysis and synthesis, concept review and baselining. Critical analysis of each subsystem as their design evolve, identifying any implication for any other subsystem. Identification of R&D needs

- Requirements and interface activities
- Validation and tests
- R&D and prototyping priorities set up
- Concept review

### 1.1.2: TDR editing (M. Lindroos, ESS)

Communication among the different workgroups, contact with the Collaboration Board, responsibility over financial management, risk management, publications and dissemination.

- Final design report

- Cost estimation
- Linac construction workplan

### **1.1.3: Review organisation** (C. Oyón, SPRI)

Planning and control of objectives, scope, schedule, costs. Responsibility over the collection, edition and publication of the generated communication and reports. Continuous identification of the high priority activities with the aim of identifying the critical aspects and accordingly suiting the project planning to the actual needs of the project. Assure the coherence with the other ESS systems design update projects. Organisation of internal reviews

- Peer reviews organisation
- External reviews organisation

### **1.1.4: Planning and documentation** (C. Oyón, SPRI)

Integration, validation and maintenance of lists of parameters generated by Work Package and Work Unit leaders, to be posted in a web-based publicly available documentation system. Control and recording of the evolution of the status of parameter lists between Draft, Active and Obsolete. Validation and identification of baseline and optional linac lattice layouts that are maintained and integrated in a relational DataBase Management System. Configuration control of miscellaneous datasets that are vital to linac description, as necessary.

## 1.2 Accelerator Science (S. Peggs, ESS)

The 5 Work Units within the Accelerator Science Work Package – Project Management, Beam Physics, Control Systems, Beam Instrumentation, and RF Modelling – will work with other Work Packages, with all ESS Divisions, and with the ESS Project Management team, to describe an ESS Linac baseline. This Work Package will work especially closely with the Management Coordination Work Package to identify and perform high-priority analyses and simulations that will be critical to determining the most suitable parameters in terms of performance, reliability and feasibility.

The baseline design will be accompanied by the smallest possible set of potential design variants, consistent with R&D and prototyping efforts that will extend beyond the 2012 Work Package completion milestone, when the Technical Design Report will be delivered. Work Package 2 activities will support and will be integrated with Physics design efforts at all ESS collaborating and other partner institutions.

### 1.2.1: Management and TDR (S. Peggs, ESS)

- Meetings planning
- Progress monitoring
- Contributions to the parameter lists.
- Definition of prototyping requirements
- TDR writing
- PBS description
- WBS description for construction phase
- Cost estimation

### 1.2.2: Beam physics (H. Danared, ESS)

This Work Unit will perform detailed studies of beam dynamics and lattice layout issues for the ESS linac. It will develop end-to-end lattice layouts and a Relational Database Management System amenable to efficient and robust project-wide configuration control. Different, consistent views (formats) of lattice layouts will be made available to the spectrum of users in other Work Packages at all ESS collaborating institutions. Steps in defining the basic layout of the linac include:

- single-particle longitudinal modelling producing a baseline layout which defines the number of superconducting cavities and cryomodules, the synchronous phases and the cavity gradients
- single-particle transverse modelling giving a baseline for the magnet lattice, transverse focusing and the rms beam size
- interaction with other work packages, in particular WP6 on beam parameters and interfaces between normal conducting and superconducting linac and WP8 on beam parameters and interfaces between linac and HEBT
- studies in close collaboration with the HEBT Work Package on the design of an optimized linac/target interface, possibly including a chicane or dog-leg system to ameliorate back-streaming neutrons and gammas

Detailed modelling and three-dimensional multi-particle simulations with space charge are required to get a more complete understanding of emittances, acceptances, losses and other factors determining the performance of the linac. Tasks in this category include:

- three-dimensional simulations investigating longitudinal acceptance
- studying effects of functional loss of cavities or cryomodules and investigating schemes for compensating such losses by redistribution of cavity gradients in the linac
- simulation of halo growth and determination of machine settings minimizing halo size in contrast to rms beam size
- investigation of requirements on beam instrumentation to set specifications on sensitivity, resolution, etc.
- code benchmarking and development

In a real linac, all beam and hardware parameters will be subject to errors or uncertainties. The study of such errors and their effect on the proton beam as well as strategies for their mitigation are an important part of the design work. Sensitivity to such errors will be used as input to hardware specifications. Examples of error studies concern:

- longitudinal errors and reduction of longitudinal acceptance resulting from static or dynamic errors in cavity gradients and phases
- transverse errors, transverse acceptance and halo growth resulting from static or dynamic errors in cavity gradients and phases (through effect on rf defocusing) and quadrupole currents, misalignment of cavities and, most importantly, misalignment of quadrupole magnets
- magnetic-field errors, such as higher multipole components of quadrupole magnets
- sensitivity to higher-order modes in accelerating cavities
- sensitivity to fluctuations in beam current
- feasibility of control loops to compensate for dynamic errors in beam or hardware parameters

Non-linearities in the beam dynamics as well as the intrinsic distribution of particles from the ion source make beam collimation necessary in order to manage beam losses and to concentrate the losses to specific points in the linac. Collimation can be performed transversally by introducing physical apertures, preferably in several stages, and longitudinally by adjusting cavity parameters such that the longitudinal acceptance has minima at selected positions down the linac:

- design of longitudinal collimation
- design of transverse collimation

Although the tasks above refer to the baseline design with 50 mA, 20 Hz and 5 MW, it is important to foresee consequences on linac layout and beam dynamics for different upgrade scenarios. For the time being, three upgrade scenarios are considered, consisting of an increase of the beam current to 75 mA while other main parameters are constant, the addition of a second target station which implies interleaving of pulses at 40 Hz and a short-pulse target which requires an  $H^-$  linac:

- 75 mA upgrade study
- second target station upgrade study
- short-pulse option upgrade study

### 1.2.3: Control systems (G. Trahern, ESS)

This Work Unit is partially defined in the “ESS Control System Study” document (hereafter referred to as CL/CSS) that became available on March 31, 2010. This document includes a preliminary integration strategy from consoles to equipment control access points.

Assumptions include:

- EPICS implementation of a 3-layer architecture
- deferred specification of the upper (user interface) layer
- Linux operating system in the middle (services) layer
- a standard “Controls Box” defining the boundary interface between the control system and the lower (equipment) layer will be implemented, prototyped, and made available to all Linac sub-systems well before the end of 2012
- broad use of a Relational Database Management System (RDBMS) as well as other information control systems, consistent with the Beam Physics Work Unit
- a distributed ESS Controls development environment, to collect and standardize sub-system controls and software development

This Work Unit will provide prototype Control Boxes (CL/CSS 3.2) to ESS collaborating institutions working on ESS Work Packages. The development of the Control Box and its methodology will be ongoing during the project. The availability of Control Boxes will:

- enable rapid deployment of a useful (equipment level) controls environment
- administer consistency between sub-systems
- minimize throw-away hardware and software development
- encourage and enable the rapid maturation of the Controls Box implementation through feedback from engineering subgroups

This Work Unit will collaborate with WP8 regarding fast Low Level RF (LLRF) controls (where interfaces with the Linac control system are recognized) as well as Master Clock timing signal generation and distribution.

An early deliverable is a document defining the Naming Convention and its scope for the naming of devices, signals and equipment. In addition we will develop software that can be used by the ESS collaboration to implement the naming scheme as sub-systems mature.

We will explore the relationship of this scheme to possible constraints vis a vis equipment tracking systems provided within the EDMS suite.

The Naming Convention will be defined as this Work Unit investigates and initiates collaboration with other projects, e.g., SNS, XFEL, ITER, SPIRAL 2 & FRIB. The scope of these collaborations can and should evolve beyond the mode of 'lessons learned' and include ESS systems development.

This Work Unit will collaborate with other members of ESS to produce a design document for the scientific and technical computing environment for the Linac Division. The control room software and frameworks described in CL/CSS 3.5-3.7 can provide guidance for this design. The scope of this environment shall include software used for modelling of the Linac, engineering sub-system prototyping, and control room applications as well as the support systems and personnel required for a fully robust research laboratory.

A project management system as discussed in CL/CSS 2.2 should be identified and installed early. In particular the system used to manage schedule and cost should be integrated with issue

and request tracking if possible. Suitable vendors should be found to supply the infrastructure. While there is a need for unified (i.e, project wide) project management systems, ESS should allow different software systems to be used where justified – particularly if such systems can be carried forward into the construction and operational phases of the project after the design update.

A specification document for the Control System will be produced by this Work Unit in two parts: a prototype specification document at the end of the second year, and a final document to be included in the design update report (TDR). The prototype specification will provide a sufficiently detailed proposal for the Control System so that a detailed review of it should allow the final report to be written with confidence. One deliverable of this effort in tandem with the project management developments should be a Work Breakdown Structure (WBS) for the Control System design.

This Work Unit will also establish the relationship of Linac and Target controls and will also define its role with respect to :

- Machine Protection System (MPS)
- Personnel Protection Systems (PPS)

#### **1.2.4: Beam instrumentation** (A. Jansson, ESS)

This Work Unit will design and prototype linac beam diagnostic instrumentation, including beam loss monitors, beam current monitors, beam position monitors, transverse and longitudinal beam profile monitors, emittance scanners, and a time-of-flight measurement system. It will:

- interface with the Beam Physics Work Unit, and with the Spoke, Elliptical, Front End, and HEBT Work Packages, to specify the beam instrumentation needs in each part of the linac, and determine the relative priority of each system (e.g. essential for machine protection, or useful for performance optimization)
- develop a minimum set of different beam instrumentation designs for each function
- participate in cryomodule design and prototype testing to the extent the linac design requires some instruments to be located inside the cryostat.
- interact with the HEBT Work Package and with the ESS Target Division to design instrumentation for beam observation on the target, and for beam-on-target tuning
- work with the Control Systems Work Unit to provisionally define instrumentation data acquisition interface standards.

### **1.3 Infrastructure and services (J. Eguia, Tekniker)**

The overall objective is to perform the design and dimensioning of all infrastructure facilities and services, including HVAC (Heating, Ventilation & Air Conditioning), cryo-plants, cryodistribution system, supply of cooling water, electricity, and networking. ESS will be a climate-neutral and sustainable facility, with WP3 responsible for the liaison with the ESS energy engineer team. As a design philosophy, innovative design choices are requested to assure an efficient heat recovery system to supply “high quality” heat to the Lund district heating system.

#### **1.3.1: Management and TDR (J. Eguia, Tekniker)**

This work unit will take charge of the internal control and revision of activities, to ensure the quality of the deliverables and the fulfilment of milestones. It will also control the cumulative costs and the resources deployed in every other work unit, whereas monitoring the timetable to ensure that activities are carried out as planned, and outcomes prepared in due time. At a general level, this work unit will be responsible for the interfacing with the different teams working inside the WP.

Since the work package is rather horizontal in technologies, not too demanding in terms of R&D and organized in parallel work units and disciplines, the management of the whole structure will be carried out in a separate work unit, speaking on behalf of the whole workpackage specially with those partners acting as reviewers and supervisors, namely SNS and DESY. On the other hand, closer collaborators and contacts will be managed by each work units, whit the present remaining as ultimate responsible for decision making and conflict solver.

Finally, this work unit will also integrate teams working in parallel in different countries (Sweden, Spain, France, Switzerland, Germany and the USA), which demands strong leadership and specific management expertise.

An additional important activity will be collecting the necessary information to update and deliver a comprehensive PBS and WBS for the construction phase. And, last not least, this work unit shall collect, elaborate, prepare and deliver the necessary data to complete the Technical Design Report at a LINAC level. Such a task has been identified as critical and deserves a unique block in the Work Breakdown Structure of the workpackage.

To sum up, the key activities of the work unit are:

- Meetings planning
- Progress monitoring
- TDR writing
- PBS description
- WBS description for construction phase
- Cost estimation

#### **1.3.2: Electrical systems (F.L. Garcia, Tekniker)**

This work unit will perform the outline definition of the electrical system necessary for the LINAC of the European Spallation Source, with the objective of supplying energy in the amount,

quality and requested, to the systems that request it. It will determine the electrical needs and the proposed solution for supply for the linear acceleration, including the necessary equipment to supply and drive the RF power and the power supply for the electro magnets that the LINAC comprises. In parallel, a baseline design of the distribution system will be developed.

ESS shall be a sustainable facility, climate neutral, with energetic efficiency and energy recovery as major topics in the agenda of the design. Therefore, this work unit will seek innovative solutions for the power supply and distribution, whilst offering the necessary interface and support to the ESS-Energy Team. A shared design work is planned, with strong contributions and links with the local (Lünd) and other relevant governing bodies.

The electrical supply definition of the cryoplant will be covered in the work unit related to cryogenics and, thus, remains out of the reach of this task.

### **1.3.3: Vacuum system** (J,Eguia, Tekniker)

This work unit will develop the vacuum generation system for the whole LINAC of ESS. With a view to lowering beam – gas interaction and supplying the requested environment at the requested places, this work unit will perform the general design and the detail component selection of the vacuum system, detailed enough for an accurate cost estimate and an efficient stock-up of components during construction phase.

Such design shall receive or otherwise get input such as the control strategy and the definition of security procedures for both machine and operator safety from the Control Group, thus providing a control interface for system engineering and a sensible alignment with the control strategy of the complete facility.

This work unit will remain in contact with beam-dynamics activities of the LINAC (WP2) in order to foresee, evaluate and monitor the effects of gaseous species over the performance of the accelerating structures and the beam, which will become a critical input for the operation of the vacuum system.

Finally, the WP will support and coordinate the creation of a vacuum team in Lünd to oversee, define and control the construction, operation and maintenance of the vacuum system during construction phase, and take the lead in the commissioning, whereas building the necessary expertise in house.

### **1.3.4: Heating, Ventilation and Air Conditioning** (R. Enparantza, Tekniker)

The definition of the heating systems and ventilation necessary for human comfort will be performed in this work unit. Special requirements dealing with air conditioned areas (be it assembly points, metrology areas etc.) will be identified and dealt with.

The present activity deals with human-required heating, ventilation and air conditioning needs, not with equipment-driven cooling needs. Safety considerations (action in case of fire, evacuation pathways, procedures to handle contaminated air, segmentation of ambient etc.) will also impact and determine the baseline design of the HVAC system, which will be performed in this work unit.

Therefore, this WU will have strong relations with the Conventional Facilities group, since the result of this definition will be a critical input for the planning of buildings and construction phase.

### **1.3.5: Auxiliary Equipment** (I. Ariz, Tekniker)

This work unit will perform the follow-up and definition of auxiliary equipment of moderate/high importance that shall be needed at the ESS LINAC. This task will not only plan “in-operation” needs, but it will also detail the infrastructure and services that will be needed during the construction phase.

A critical activity within this work unit is that of deciding, defining, and designing the “site-specific” design features, operation procedures and the criteria behind the maintenance operations. The final objective is to develop the basis of an ESS-philosophy for the design and construction phase. For this, a thorough study will be performed in existing facilities, to establish the rationale for the design choices, in order to transfer as much from the existing experience to ESS and thus create a site-specific identity in ESS, as backbone for the global infrastructure design. Modularity, maintenance philosophy, physical configuration of items, pits and escape routes and so many others can’t be decided solely under machine-related conditions, but as a result of global decisions that create the underlying coherence of the design effort. Therefore, this activity will create a general framework and the basic aspects of the design philosophy of the ESS.

Special care will be put in the link with other systems of the facility, namely ion sources, target station and instruments, in order to avoid overlapping and duplicating equipment and efforts.

Some other issues that this work unit will deal with include: the alignment of accelerating structures, modules and magnets with respect to previous structures; overall configuration of LINAC tunnel to avoid interferences and colliding elements; cranes, rail systems and so forth. This work unit will also define different prototypes for work unit 8 to develop and ensure the feasibility of the infrastructures systems.

### **1.3.6: Cooling systems** (J. Alonso, Tekniker)

Within this work unit, the issue of refrigerating a LINAC like that of ESS will be addressed. In order to create a MW proton beam, the apparent power can be as high as 60 – 70 MVA, which means that the amount of dissipated power is enormous. This unit will foresee and plan the refrigeration system that will evacuate heat when needed and in the amount needed.

In accordance to the overall design philosophy of ESS, the excess heat will be reused (when dissipation temperatures make it possible) to feed the heating systems both at ESS and Lünd itself. For this, an exergy analysis will be performed to actually study how much energy could be profitable from the excess generated at ESS. Therefore, strong links are needed with the Energy Team and the local authorities to ensure a global strategy for real improvements in energy recovery figures and plan innovative solutions to serve this general objective.

### **1.3.7: Cryogenics** (W. Hees, ESS)

This will perform the outline design of the cryogenic systems that will feed the ESS LINAC in its superconducting parts, activity which will be divided in two: 1) The Central Cryoplant and 2) The Fluid Distribution System for the cryomodules.

The design of the cryoplant is the main issue to be solved within the work unit. The Central Helium Liquifier System will be calculated and designed with the inputs on heat loads from the responsible partners of the superconducting linac, based on the cryomodule performances and estimation from static and dynamic performances. Alongside with the calculations, fluid cycles, liquefaction systems and necessary equipment will be defined, with the help of vendors and stakeholders. With an overall design of the distribution system, fluid requirements (both He and N) will be defined, and the related dewar systems, containers, intermediate buffers etc. A preliminary study of the operation mode of the cryoplant will also be performed to integrate the control philosophy of ESS, defined by the Control Group. Strong collaboration from industry is necessary and expected in this phase..

From this cryoplant, the liquid helium distribution system will also be planned. A general layout of the piping will be generated with ancillary systems and equipment, specially cryovalves and flow-meters. Solutions for thermal deformations (lumped vs. distributed) will be planned in advance.

Special attention will be paid to the interface with the cryomodules and the cold boxes for they are the critical elements that will define the performance of the cryomodules and thus the requirements of the complete cryo-system. The design and definition of the cryogenic elements of the modules remain outside the scope of this work unit, and will be addressed in the WPs developing the superconducting accelerator structures.

And last, but not least, this work unit will support and coordinate the creation of a strong cryogenic team in Lünd to oversee, define and control the construction, operation and maintenance of the cryoplant and the cryo-distribution system during construction phase, and take the lead in the commissioning, while building the necessary expertise in house. Therefore, the leadership of the cryo-activities will eventually migrate so that, after the design update phase has elapsed, it belongs to in-house personnel in the ESS site in Lünd.

## 1.4 Spoke superconducting linac (S. Bousson, Orsay)

The Work Package 4 (WP4) of the ESS Technical Design Report (TDR) will address the engineering design of the complete spoke cryomodules which will compose the intermediate energy section of the ESS Superconducting Linac. This section is covering the energy range between ~50 MeV and ~200 MeV, and will be based on multi-gap superconducting spoke resonators at 352 MHz. The overall specifications of the spoke linac will be provided by the accelerator design team (input and output energy, cavity beta and number of accelerating gaps). The aim of this WP is to performed in 2 years (2011-2012) a detailed design of the spoke cryomodule: it includes the cavity (for the 2 b), the power coupler, the cold tuning system (mechanical and piezo), the cryomodule vacuum tank, the cryogenics and magnetic shields, the cavity supporting system and alignment, the cryo-fluid circuitry, the cryogenic valve box and the assembly toolings.

Spoke cavities are under developments in several laboratories worldwide, but up to now none of them have effectively accelerated any beams. The first part of the will consist in a detailed analysis of the spoke cavities performances state-of-the-art in order to establish the ESS spoke linac operating values (accelerating fields, cryogenic consumption, temperature operating point,...).

The work will be performed having in mind the objective of fulfilling all requirements for producing a complete TDR: for the whole ESS spoke linac, a Working Breakdown Structure (WBS), a Product Breakdown Structure (PBS) will be defined, and a cost estimate at 20% will be calculated.

Early prototyping will be included in this work to validate part of the cavity and power couplers design and to justify the cavity design gradients. At the end of 2012, 2 spoke cavity prototypes and 2 power couplers will be constructed and partially tested.

### 1.4.1: Management and TDR (S. Bousson, Orsay)

This WU is dedicated to the WP management and the non-technical work that is required for fulfilling the requirements of a TDR:

- Overall management of the WP : planning meetings and progress monitoring
- Preparation of the PBS of the spoke linac section
- Preparation of the WBS of the spoke linac section for the construction
- Define and fill a parameter list for the spoke linac section for a better exchange between the accelerator design group (beam dynamics), the RF WP and the engineering design of the spoke linac elements
- Organize the TDR writing work
- Define the prototyping requirements, strategy and cost for the project phase between the TDR and construction.
- Perform the spoke linac costing from the PBS and WBS

### 1.4.2: Cavities (G. Olry, Orsay)

The main activities within this WU are the following:

- Establish a state of the art for the spoke cavity design and performances, in particular looking at the recent developments in this field for the EURISOL and HINS projects. This will be used to address two main questions:
  - what cavity performance (Eacc) should be taken as the design goal
  - address a pros and cons comparison between operation at 4.2 K and 2 K
- RF Engineering design of the different spoke cavities (for all required beta), and if possible comparison of the results with several electromagnetic codes
- Mechanical design of the cavity
  - helium tank
  - stiffening system
  - cold tuning system

During this study, one of the main goal will be to minimize the dynamic lorentz forces detuning. All technical choices should be done and justified by the positive impact on this key parameter for a pulsed machine.

Specify what preparation and conditioning procedure should be performed in order to reach the design performances of the spoke cryomodule:

- Procedures for the cavities:
  - chemical etching requirements for the cavities (standard BCP or electro-polishing)
  - cavity cleaning procedure (H degazing, in-situ baking, high pressure water rinsing)
  - requirements for cavity assembly in clean room
  - special processing procedure during individual cavity testing (He processing)
- Power coupler preparation
  - Procedure for power coupler cleaning and assembly
  - Power coupler conditioning (with high RF power)
- Requirements for cryomodule assembly (clean room)

#### **1.4.3: Cold tuning system** (N. Gandolfo, Orsay)

The aim of this Work Unit is to develop the cold tuning system (CTS) for the spoke cavities. The CTS is a device required to in-situ (inside the Cryomodule) adjusts the cavity resonant frequency to the nominal value. For the spoke cavities, two options for the cold tuning system will be considered:

- A “classical” CTS based on a mechanical deformation of the cavity length to adjust the frequency. Such systems have already been developed for single-spoke resonator for the Eurisol project.
- A novel concept for superconducting cavities, based on a niobium plunger inserted inside the cavity volume. This new scheme has been developed for the Spiral-2 project on the high energy quarter wave resonators.

Both systems will be envisaged and studied from a conceptual point of view. One solution will be then chosen and studied into details to perform a complete engineering design of the CTS for the spoke cavities.

#### **1.4.4: Power coupler** (E. Rampnoux, Orsay)

- Precise the technical specifications:

- Required transmitted RF power
- Needs for adjustable or variable coupling
- Power coupler RF design, taking into account:
  - Ceramic window geometry and number
  - Cooling requirements

#### **1.4.5: Cryomodule** (G. Rouillé, Orsay)

- Perform the mechanical and cryogenic design study of the module (could be for 4.2 K or 2K, depending on the WU 3 conclusions). Assess the cryogenic performances of the module. This work will be done in 2 phases:
  - Conceptual design, in order to start the work before having all precise data from the others WU
  - Detailed engineering design
- Cold box design for the cryo-fluids exchange with the module
- Magnetic shielding design
- Vacuum system
- Study and define the alignment procedure
- Particularly study the module required cooling time in order to assess the need for a cavity baking (avoid 100 K effect)
- Perform the conceptual design study of the assembly tooling

#### **1.4.6: Superconducting magnets** (G. Rouillé, Orsay)

If the focusing elements are chosen to be cold, the integration of the superconducting magnets (developed in WP5) in the spoke cryomodules will be addressed in this WU. It will take into account the mechanical integration, the study of the supporting and alignment systems and the integration of the power supply feed through for the magnets.

#### **1.4.7: Prototypes and tests** (G. Olry, Orsay)

With the given timeframe, the possibilities for prototyping and testing are limited. The prototyping should concentrate on the fabrication and test of 2 cavity prototypes (one for each b), and 2 power couplers.

- Cavity prototyping outcomes:
  - Assess the fabrication procedure, and evaluate the tuning procedure, check the capability of reaching the desired frequency, evaluate the major difficulties during fabrication.
  - Assess the preparation procedure (chemistry, baking, clean room assembly)
  - Test in vertical cryostat (at 4K and 2K) and assess the cavity performances (accelerating field, Lorentz forces detuning coefficient, dissipated power) at the two temperatures.
- Power couplers outcomes:
  - Assess the fabrication procedure, evaluate the major difficulties during fabrication.
  - Measure the couplers main parameters (f, S-parameters...)
  - Assess the preparation procedure (cleaning, clean room assembly)

- Depending on the availability of a 352 MHz RF power station and conditioning test bench, a coupler conditioning with the necessary RF power (2 or 4 times the nominal power) could be envisaged to assess the overall coupler performances.

## **1.5 Elliptical superconducting linac (G. Devanz, Saclay)**

The ESS proton linac consists in a room temperature low energy part up to the transition energy. Beyond this point the acceleration is taken over by superconducting (SC) structures. The first SC section consists in two families of spoke cavities modules, then from 200 MeV two families of 704 MHz elliptical SC cavities, grouped into 8-cavity cryomodules. The first 5 modules host 8 beta=0.65 5-cell cavities each (medium beta) and the 12 last module host 8 beta=0.92 5-cell cavities each (high beta).

The main objective of the WP5 of the design update phase is to provide the engineering design of the fully equipped cryomodules for both medium and high beta elliptical cavity sections of the ESS linac operating at 2K with an accelerating field of 15 MV/m.

The cryomodule design will include all aspects, including the valve box, internal Helium distribution, thermal shielding, the cavity alignment and supporting systems. The design should be carried out in close collaboration with the SPL development of a prototype cryomodule housing 4 beta=1 elliptical cavities. In order to guaranty the performance of the cavities in terms of accelerating gradient in long cryomodules, the cavity string is assembled in a large clean room to prevent field emission operation. It is then transported to an assembly area where it is inserted in the vacuum vessel. The whole assembly sequence requires large tooling equipment which will be studied in conjunction with the cryomodule design. The high and medium beta ESS elliptical modules should be sharing the same design, the prototyping effort will therefore be concentrated on the high beta module in the next phase of the project.

WP 5 will provide the design of the 704 MHz superconducting elliptical cavities, helium tanks, power couplers, high order mode couplers, frequency tuners, magnetic shielding. At the end of the design update study, CAD models of fully equipped modules will be produced. Several components, namely high beta cavities, fundamental power couplers and fast frequency tuners are considered as critical, therefore prototypes will be fabricated for each of them, and tested after the design update phase. Similar objects have been developed for SNS and during the last decade in European Framework Programs in several laboratories. The feasibility of components of the same type, at the same operating frequency has been demonstrated, and their performance goals already met experimentally, however with small statistics.

WP5 will provide the section relative to the elliptical section of the technical design report describing all of the above including a cost estimate with a 20% accuracy at the end of 2012.

### **1.5.1: Management and TDR (G. Devanz, Saclay)**

**1.5.1.1:** WP management, planning of the design update follow-up and construction phase, including PBS and WBS.

**1.5.1.2:** TDR write-up and costing coordination.

### **1.5.2 : Medium beta cavities (G. Devanz, Saclay)**

**1.5.2.1:** RF and mechanical study of the medium beta elliptical cavities and helium tank.

**1.5.2.2:** RF and mechanical design of the HOM dampers according to the damping specifications provided by WP2.

**1.5.2.3:** Design of the magnetic shield of the medium beta cavity.

**1.5.2.4:** Write-up of TDR section on medium beta elliptical cavities, including costing.

**1.5.3: Cold tuning system** (G. Devanz, Saclay)

**1.5.3.1:** Mechanical design of a cold tuning system for the elliptical cavities.

**1.5.3.2:** Write-up of TDR section on the cold tuning system, including costing.

**1.5.4: High beta cavities** (J. Plouin, Saclay)

**1.5.4.1:** RF and mechanical study of the high beta elliptical cavities with its helium vessel.

**1.5.4.2:** RF and mechanical design of the HOM couplers according to the damping specifications provided by WP2.

**1.5.4.3:** Design of the magnetic shield of the high beta cavity.

**1.5.4.4:** Design and fabrication of the RF tuning bench.

**1.5.4.5:** Write-up of TDR section on high beta elliptical cavities, including costing.

**1.5.5: Power coupler** (G. Devanz, Saclay)

**1.5.5.1:** RF and mechanical design of the 1.2 MW, high duty cycle power couplers. It will be compatible with the upgrade of ESS, within the limit of 10% duty cycle.

**1.5.5.2:** RF and mechanical design of the coupler conditioning bench.

**1.5.5.3:** Write-up of TDR section on power couplers, including costing.

**1.5.6: Medium beta cryomodule** (W. Hees, ESS)

The work is concentrated on the high beta cryomodule. The medium beta cryomodule will share the same mechanical and cryogenic design, assembly and alignment methods.

**1.5.6.1:** Mechanical design of the medium beta cryomodule. This phase takes into account the assembly phase of the cavity string inside the modules, vacuum and cryogenic sectorisation, mechanical and thermal loading of the system, alignment, and integration of the instrumentation and superconducting quadrupoles.

**1.5.6.2:** Cryogenic and vacuum design of the modules. This includes the detailed design of the valve box and vacuum systems.

**1.5.6.3:** Mechanical design of the clean room cavity string assembly tools.

**1.5.6.4:** Mechanical design of cryomodule assembly tools.

**1.5.6.5:** Write-up of the TDR section on elliptical cavities cryomodules including costing.

### **1.5.7: High beta cryomodule (W. Hees, ESS)**

The work is concentrated on the high beta cryomodule.

**1.5.7.1:** Mechanical design of the high beta cryomodule. This phase takes into account the assembly phase of the cavity string inside the modules, vacuum and cryogenic sectorisation, mechanical and thermal loading of the system, alignment, and integration of the instrumentation and superconducting quadrupoles.

**1.5.7.2:** Cryogenic and vacuum design of the modules. This includes the detailed design of the valve box and vacuum systems.

**1.5.7.3:** Mechanical design of the clean room cavity string assembly tools.

**1.5.7.4:** Mechanical design of cryomodule assembly tools.

**1.5.7.5:** Write-up of the TDR section on elliptical cavities cryomodules including costing.

### **1.5.8: Superconducting magnets (M. Bruchon, Saclay)**

**1.5.8.1:** Magnetic and mechanical design of the two types of SC quadrupoles.

**1.5.8.2:** Write-up of TDR section on SC quadrupoles.

### **1.5.9: Prototypes and tests (G. Devanz, Saclay)**

**1.5.9.1:** Design and Fabrication of the coupler test box

**1.5.9.2:** Fabrication of a pair of 1.2 MW power couplers

**1.5.9.3:** Design and fabrication of a room temperature tuning bench for elliptical cavities equipped with the interface parts for the high beta cavities.

**1.5.9.4:** Design and fabrication of the tools required to perform the chemical etching of the cavity and clean room preparation.

**1.5.9.5:** Fabrication and preparation of two high beta cavity prototypes. In order to build these prototypes during the design update phase, they will not be equipped with HOM couplers

## 1.6 Normal conducting linac (S. Gammino, Catania)

Design of the elements of the front-end up to the warm-cold transition (proton source, LEBT, RFQ, NC linac and chopper section).

In principle the competences necessary to take the responsibility of the design, construction and integration of the whole NC part of the linac, from the high current proton source to the normal conducting DTL up to 50 MeV, exist in different laboratories, in particular at INFN and at CEA.

A strong synergy between these two institutions and ESS-Bilbao, with possible contributions from others, may permit to fulfill the requested update of the design for the Front End and NC linac and to set the basis for the construction of the above mentioned components.

For some of these components the construction of prototype could be convenient in principle, for some others the experience gained by the research teams involved in the project may permit to skip the construction. In particular for the Ion Source and LEBT the existing equipment may provide a valuable test bench but the construction of an ‘ongoing prototype’ is to be considered in the following, or immediately following a 3-month tests of Ion source+RFQ.

This ‘long run’ experience will put in evidence any possible criticality and will permit to optimize the design of these components.

The design study of RFQ-MEBT-DTL can take advantage from the experience on the design of a similar linac (LINAC4), from the experience of the TRASCO and IPHI RFQ, and of the DTL prototype built by INFN-LNL and CERN. The MEBT line, matching the RFQ beam into the DTL, very important for the performances of the entire linac, would be designed to ensure phase advance matching between RFQ and DTL; such matching is space charge independent at first approximation.

### General remarks

The major challenge of this part of the accelerator is the preparation of a high quality beam, with a pulse well defined in time, a short emittance and a minimized halo, so that the beam losses throughout the high energy part of the linac could be limited and the overall ESS reliability be maximized. In order to prepare a high quality beam, not only the source extractor design, the RFQ modulation and the first cells of DTL are relevant, but also the LEBT and MEBT with their chopping systems, the necessary diagnostics, steerers and collimators.

Beam dynamics aspects related to the choice of the focussing period, steering dipoles location and possible beam position monitor integration must be properly studied and addressed in the TDR.

The possibility to take into account future upgradings of the project at this early stage is to be evaluated, especially for what concerns the civil engineering design. Some areas should be over-dimensioned and in this sense the area that will host the Front-End should take in consideration the possibility to modify the injector in future, e.g. with a more complex MEBT.

### **1.6.1: Management and TDR** (S. Gammino, Catania)

The activities are essentially the coordination of the work of all the other WUs and the communication with the other WPs, in order to ensure the consistency of the WP6 work with the project plan.

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 is in charge of the coordination and harmonization of the physical design and beam dynamics of the initial part of the linac, defines and manage the internal interfaces between WUs. This WU coordinates the writing of the technical design report (TDR) for the parts of interest, including the technical drawings of each component and a full cost analysis with a precision better than 20%.

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

### **1.6.2: Proton source and Low Energy Beam Transport** (L. Celona, Saclay)

INFN-LNS (Catania) and CEA-Saclay may be able to contribute to the design of the injector part (the proton source and the LEBT) in close collaboration. The high current proton source will be based on the know-how acquired during the design phase and the construction phase and commissioning of the sources named TRIPS and VIS at INFN-LNS and of the SILHI source at CEA-Saclay, but surely some remarkable improvements are to be developed because of the high current at a relatively low extraction voltage. A new extraction system has to be developed for a pulsed beam of about 60 mA with a quite low emittance as required by the following RFQ. An option for larger current will be considered.

A new design of the magnetic field profile is essential and the microwave injection system will be deeply revised according to the recent experience gained with the VIS source. A new idea to enhance the electric field in the plasma chamber will be tested in order to get higher ionization rates. Further studies about brightness optimization are mandatory, which can be carried out either at CEA and at INFN-LNS.

A series of tests will be carried out in the 1<sup>st</sup> year concerning the possible use of different frequency than 2.45 GHz, that is the standard frequency used up to now for similar sources.

The LEBT from the source extractor to the RFQ entrance must take into account different and competitive requests as it should be as short as possible and it should permit to allocate the necessary diagnostics and the low energy chopper. These achievements are to be obtained for a low energy beam with a power of about 5 kW and the optimum matching with the RFQ must be guaranteed. A remarkable R&D is available from the studies carried out at Saclay and at Catania, in particular some of the considerations which are valid for the IFMIF project may be exported for ESS Linac LEBT.

### **1.6.3: Radio Frequency Quadrupole** (B. Pottin, Saclay)

The design, construction and commissioning of the RFQ may be under the responsibility of CEA, Saclay, in close collaboration with INFN-LNL. In spite of the fact that a remarkable know-how is available in terms of RFQs designed for high intensity beams (IPHI, TRASCO, EVEDA), it seems envisageable to review these designs after a period of tests of pulsed mode operation at the IPHI RFQ, tailored to ESS parameters, with particular attention to the long term reliability (e.g. 3 months) with a duty factor of 20 Hz and 2 ms pulse length.

An acceptance of  $0.25\pi$  mm mrad can be considered at this stage, but this item needs to be studied along with the reliability and the power dissipation, to be optimized. As for the construction of the RFQ, industrial experiences are available in France and in Italy.

The existing effort for prototyping and realizing structures on the above mentioned projects can be directly reused for the TDR and none major specific prototype is identified for ESS.

It must be remarked that a few differences exist for these projects and a unique choice is needed for ESS; in particular, RFQ could be four vanes without PILs and coupling cell, very similar to Linac4.

### **1.6.4: Medium Energy Beam Transport** (I. Bustinduy, Bilbao)

This part is under the responsibility of ESS Bilbao, in cooperation with other institutions. The design of the MEBT could be simplified in a first phase, by considering a system as the one suggested by INFN-LNL and CEA people. A short MEBT line could be possible, with diagnostics and electromagnetic quads. For the future upgrading, fast chopper may be taken in consideration.

The matching between RFQ and DTL is probably a crucial point for beam halo formation. The ramping of the RFQ and DTL voltage (increasing in the last RFQ part and first DTL part) should make possible to match the longitudinal and transverse phase advance per meter, and to get a space charge independent matching.

### **1.6.5: Drift Tube Linac** (A. Pisent, Legnaro)

As for the DTL (accelerating the beam between 3 and 50 MeV), the design of LINAC4 may be a relevant basis. INFN-LNL team has already designed an accelerator with very similar performances and a common prototype tank approximately 1 m long has been prototyped by Italian industry, together with CERN Linac4 team (prototype for Linac4 and SPES driver). The collaboration with CERN team is to be encouraged and the DTL may be built on the basis of this R&D. If we look in details to the different parameters of the Linac4 and ESS DTL, there is an evident similarity concerning pulse current, gradient, injection energy; some differences exist for output energy and duty cycle only. For this reason, there is no need of prototyping for NC Linac, but a careful analysis of the optimum design, adapted to the ESS parameters, is necessary. Particularly, the beam dynamics studies and the RF design, plus the preliminary mechanical studies necessary to use the already developed DTL structures to the ESS duty cycle, will be the major activity during the TDR preparation phase.

## **1.7 HEBT, NC Magnets and Power Supplies (S. Pape-Møller, Aarhus)**

Work Package 7 is concerned with the design of high-energy beam transport, in particular beam optics, in collaboration with WP2. The design should fulfill the different functionalities of the HEBT, and interface to the exit of the linac and input to the targets and beam dump. The functionalities include transport to the main target, to a commissioning/tune-up beam dump, to optional future targets or other options to be defined, and a collimation section after the linac. Also included in the work package are considerations about bringing the HEBT into operation, i.e. a steering and a focusing concept.

In addition to the above general design of the HEBT, the Work Package should also define standards for all normal conducting magnets and the corresponding power supplies. In particular studies taking sustainability over a 10 year period are included. Finally, a prototype for a combined focusing/steering/diagnostics section for the warm interfaces between cryostats.

### **1.7.1: Management and TDR (S. Pape-Møller, Aarhus)**

This work unit consist of the WP management and non-technical work, in particular writing the TDR. It includes the following main points

- WP Management
- TDR writing
- TDR contribution
- Costing analysis
- Costing analysis report
- Construction planning
- Construction plan

### **1.7.2: High-Energy Beam Transport (S. Pape-Møller, Aarhus)**

This work unit is designing the high-energy beam transport from linac output to targets. It includes the following main points

- Beam transport and expander design
- Upgrade transport systems
- Collimation systems design
- HEBT Mechanical systems

### **1.7.3: Normal conducting magnets (S. Pape-Møller, Aarhus)**

This work unit establishes standards for all normal conducting magnets. Conceptual designs will be provided for all magnets. Radiation hardness will be included whenever needed. Sustainability issues will be included already at this stage.

- Technology analysis
- Costing study
- Conceptual design of all normal conducting magnets including:

- SC linac quadrupoles
- SC linac steerers
- LEBT magnets (solenoids+steerers)
- MEBT quadrupole
- MEBT steerers
- HEBT quadrupoles
- HEBT steerers
- HEBT dipoles
- HEBT octupoles
- HEBT duodecapoles

#### **1.7.4: Power supplies** (S. Pape-Møller, Aarhus)

This work unit establishes standards for all normal conducting magnets. Conceptual designs will be provided for all magnets. Sustainability issues will be incorporated already during this phase.

- Technology analysis
- Costing study
- Conceptual design of power supplies for all normal conducting magnets including:
  - SC linac quadrupoles
  - SC linac steerers
  - LEBT magnets (solenoids+steerers)
  - MEBT quadrupole
  - MEBT steerers
  - HEBT quadrupoles
  - HEBT steerers
  - HEBT dipoles
  - HEBT octupoles
  - HEBT duodecapoles

#### **1.7.5: Normal magnet/diagnostic prototypes** (S. Pape-Møller, Aarhus)

A prototype for a combined quadrupole/steerer/diagnostics section to operate in the warm interface sections between cryostats of the linac will be designed, built and tested.

## 1.8 Radio Frequency 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- $\beta$  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 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  $\beta$ '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.

### **1.8.1: Management and TDR** (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.

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

**1.8.1.2:** 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.

**1.8.1.3:** 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.

### **1.8.2: RF modelling** (RF group leader, ESS)

- 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.

**1.8.2.1:** 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).

**1.8.2.2:** 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.

**1.8.2.3:** 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.

### **1.8.3: Low Level RF system (A. Johansson, Lund U)**

- Investigate alternative LLRF system architectures.
- Design, build and test a LLRF system for the 352 MHz spoke cavities.
- Design, build and test a LLRF system for the 704 MHz elliptical cavities.
- Design, build and test 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.

**1.8.3.1:** 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.

**1.8.3.2:** Adopt baseline design for, then build and test the LLRF control and monitor system for the 352 MHz NC linac.

**1.8.3.3:** Adopt baseline design for, then build and test the LLRF control and monitor system for the 352 MHz superconducting spoke cavities.

**1.8.3.4:** Adopt baseline design for, then build and test the LLRF control and monitor system for the 704 MHz superconducting elliptical cavities, including control of the cavity tuner.

**1.8.3.5:** Adopt baseline design for, then build and test 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.

**1.8.3.6:** 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.

**1.8.3.7:** 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.

**1.8.3.8:** 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.

#### **1.8.4: RF power generation** (A. Rydberg, Uppsala)

- Investigate alternative RF power generation technologies.
- Design, build and test a RF power generation system for the 352 MHz spoke cavities.
- Design, build and test a RF power generation system for the 704 MHz elliptical cavities.
- Design, build and test a RF power generation system for the 704 MHz two cavities per klystron concept.

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.

**1.8.4.1:** 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.

**1.8.4.2:** Design, build and test a RF power generation system that is suitable to power a single 352 MHz superconducting spoke cavity.

**1.8.4.3:** Design, build and test a RF power generation system that is suitable to power a single 704 MHz superconducting elliptical cavity.

**1.8.4.4:** Design, build and test a RF power generation system that is suitable to power two 704 MHz superconducting elliptical cavities in parallel.

The power generation systems will be installed and used in the test facilities.

#### **1.8.5: RF Power Distribution** (A. Rydberg, Uppsala)

- Investigate alternative RF power distribution schemes.
- Design, build and test a RF power distribution system for the 352 MHz spoke cavities.
- Design, build and test a RF power distribution system for the 704 MHz elliptical cavities.
- Design, build and test a RF power distribution system for the 704 MHz two cavities per klystron concept.

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).

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

**1.8.5.2:** Design, build and test an RF distribution system to power a single 352 MHz spoke cavity.

**1.8.5.3:** Design, build and test an RF distribution system to power a single 704 MHz elliptical cavity.

**1.8.5.4:** Design, build and test different topologies of an RF distribution system to power two 704 MHz elliptical cavities in parallel from a single RF power generation system. This distribution system shall include prototype low loss vector modulators for dynamic amplitude and phase control.

The power distribution systems will be installed and used in the test facilities.