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RF Development for ESS

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Abstract

This paper gives an introduction to the RF development work required for the superconducting part of the ESS proton accelerator. It explains the development of the low level RF signal generation and the high power RF distribution and lists the different studies to be performed. In particular it concentrates on the concept to connect multiple accelerating cavities to a single klystron high power RF amplifier and the superconducting RF test facility that is required for this development work.

1 Introduction

The European Spallation Source (ESS) is a pulsed spallation source producing neutrons for scientific research which will be constructed in Lund close to the foreseen site for the future MAX IV synchrotron radiation laboratory. It consists of a proton linear accelerator, a target station and neutron beam lines for user's experiments. The neutrons are extracted in a fission process from their bound states in heavy atomic nuclei: The target would be typically liquid mercury or lead. The energy required for the fission process is created by bombarding the nuclei with high energy protons, hence the need for a proton linear accelerator. The projected time line is to have a technical design report by 2012, to start installation on-site four years later and to have the first beam by 2019.

The ESS Scandinavia organisation has been discussing with Uppsala university the possibility for support in the development phase, in particular for the design of the 704 MHz radio frequency (RF) power distribution and control system for the superconducting part of its proton linear accelerator (linac). Moreover ESS Scandinavia has suggested the study of an RF power distribution concept in which multiple accelerating cavities are powered from a single klystron RF power amplifier. Uppsala University has confirmed its interest to participate in the development work for the ESS, specifically to participate in the development of the RF system, but also at a later stage for the target system and neutron beam lines.

This paper concentrates on the development of the RF system for the superconducting part of the ESS proton linac and the RF test facility required for this development. We will first describe the basic layout of the ESS proton linac and the development objectives of the RF system. After that we will discuss in more detail the different parts of the RF system: cavities, signal generation, amplification and distribution. Based on this we will describe

Table 1: *Basic parameters of the ESS proton accelerator [1]*

Beam energy	2.5 GeV
Beam power average	5.0 MW
Beam loss rate	<1 W/m
Beam current (average)	50 mA
Beam pulse repetition rate	20 Hz
Beam pulse length	2.0 ms
Peak RF input coupler power	1.0 MW
RF frequency	
- low energy part	352.2 MHz
- high energy part	704.4 MHz

the RF test facility that is required to carry out the development work. The cavities are not part of the RF development work foreseen at Uppsala University, but a brief description is included as required for the understanding of the RF development work.

2 The ESS Proton Linear Accelerator

The specifications of the ESS are based on two scientific requirements: (a) to deliver the same amount of neutrons in time average as ILL and (b) this at a pulse repetition rate low enough to avoid loss of efficiency for this high flux even for the slowest neutrons [2], as experiments with different velocity neutrons require different time intervals between consecutive pulses [3]. A previous proposal for a possible layout of the ESS was published in 2003 [4]. This was based on a $16^{2}/_{3}$ Hz 5 MW long pulse target station, directly behind a 1.3 GeV proton linac, and a 50 Hz 5 MW 1.4 μs short pulse target station behind a pulse compressor ring. Both target stations would have 20 instrumented beam lines each. At present only a 5 MW long pulse target station is considered with 2 ms pulses at a repetition frequency of 20 Hz: a 5 MW LP ESS [2].

The key elements of the ESS proton linac are shown in figure 1 and some key parameters are listed in table 1 [1]. The proton linac can be seen as three parts: the front-end that includes particle source and buncher, a low energy normal conducting linac and a high energy superconducting linac. For optimal use of well established technologies the RF frequency used for acceleration is chosen as 352 and 704 MHz. RF acceleration technology at 352 MHz

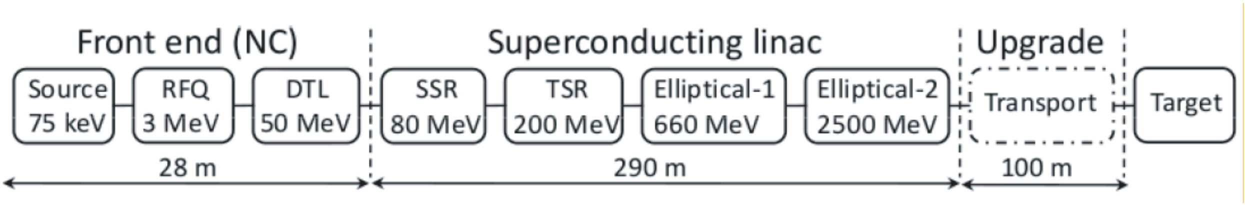

Figure 1: Key elements of the ESS proton linear accelerator [1]. The normal conducting (NC) front end and the superconducting spoke cavities (SSR and TSR) are operated at 352 MHz. The superconducting elliptical cavities are operated at 704 MHz. The "Transport" section is reserved for future a upgrade to 7.5 MW while keeping the beam energy constant at 2.5 GeV.

has been developed for the CERN LEP accelerator and is also used for the new CERN Linac 4, a normal conducting proton linac presently under construction, due to the availability of 352 MHz klystrons at CERN. A frequency jump to 704 MHz for the superconducting linac part decreases the elliptical cavity dimensions and the RF filling (and decay) time. The same frequency jump is chosen for the CERN SPL [5], a design project for a future extension of the CERN Linac 4 and part of the upgrade project for the LHC injector chain. Important synergy in development and construction is expected between the ESS and the CERN Linac 4 and SPL. The final requirements are however not similar due to higher beam power and current for the ESS and higher beam energy for the SPL (base design for 20 mA, 4 GeV, 0.2 MW) [6].

Figure 1 shows the different building blocks used in the proton linac. From left to right, there are first the ion source and RF quadrupole (RFQ) that form the front-end of the linac. The front-end creates a train with bunches of protons. Size, filling factor and distance between the bunches are critical for correct acceleration in the linac. The linac is constructed of different types of accelerating cavities optimized for the energy and thus speed of the particles to be accelerated. First is the drift tube linac (DTL) which accelerates to 50 MeV, normal conducting and operating at 352 MHz. Then come superconducting single and triple spoke resonator cavities (SSR and TSR) and finally two types of elliptical superconducting cavities that accelerate the proton beam up to its final energy of 2.5 GeV. In addition diagnostics and magnets are required to monitor and manipulate the beam inside the accelerator. A future update of the linac to higher output power by increased beam current will enhance the beam loading in the cavities and lower the acccelerating gradient at constant input power. The input power is limited by the maximum power allowed on the power couplers, in the present design around 1 MW, as there is only one power coupler foreseen per cavity. The high-β elliptical cavities are operated at this limit and therefore require an increase of their number to reach the same accelerating gradient and thus beam energy at the end of the linac. Hence the reserved space for a future upgrade.

Not shown in figure 1 are the services required to operate the linac. Besides the basic electricity, (compressed) air and cooling water, it needs a vacuum system, liquid helium cooling for the superconducting cavities and RF power to drive the accelerating cavities.

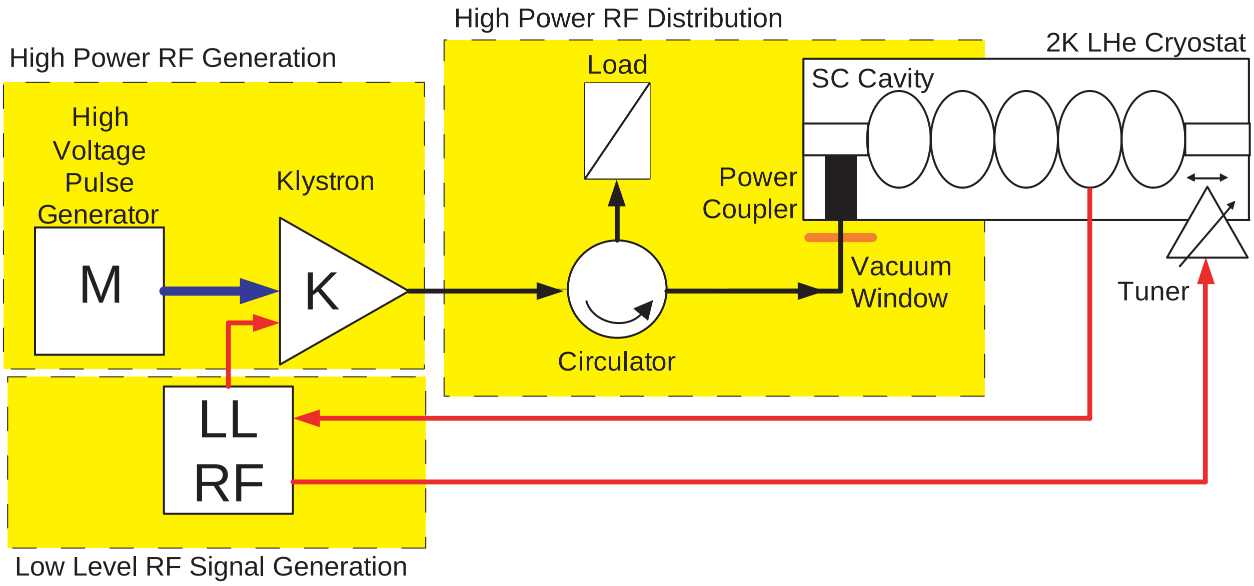

Figure 2: Basic layout of the RF system.

3 RF Development Objectives

Figure 2 shows the basic layout of the RF system. It consists of a low level RF (LLRF) signal generation part that creates the RF signal, a part that amplifies the RF signal to high power and a part that distributes the RF power to the accelerating cavities. The LLRF part monitors the RF signals in the accelerating cavities and includes a feedback and feedforward system that controls the generated RF signal accordingly. It also controls a mechanical tuner for the accelerating cavities. The high power RF part is a main cost driver in the system, both for construction and operation. The efficiency from wall power to beam power of the proton linac is mainly determined by the high power RF amplifiers, power couplers to the cavities and acceleration efficiency in the cavities.

The superconducting accelerator cavities are designed for an accelerating gradient of 15 MV/m at a peak power of 1 MW. This is far less than the 59 MV/m gradient achieved in a single cell cavity or the >28 MV/m average achieved in 1.3 GHz TESLA/ILC type 9-cell cavities [9]. The achievable gradient is in limited by power dissipation by field emission electrons, multipacting (resonant electron multiplication) and breakdown of the RF field. Uppsala University carries out research on the RF breakdown on normal conducting cavities (see e.g. [10]). A natural extension of these activities to superconducting cavities are thermometry studies of cavities under RF breakdown [11].

Due to the extremely high quality factor and correspondingly small bandwidth, the cavities are extremely susceptible to mechanical perturbations. Either by ambient noise, causing so-called microphonics, or by Lorenz force detuning which is caused by the radiation pressure of the high power RF pulse in the cavity. It causes a frequency change that can be significantly larger than the cavity bandwidth [11]. Both effects can be alleviated by mechanically stiffening the cavities, but also by an active piezoelectric compensation system (tuner) that can moreover also compensate for slower thermal drifts [12, 13]. The compensation is most important for the low-β cavities where the protons have lower energy. As these are shorter they have lower power per cavity and are therefore more efficient to operate with more cavities per klystron. In the high-β cavities the protons have a higher energy and therefore regulation is critical while at the same time these cavities have a higher power level and would therefore be operated with fewer cavities connected per klystron. The individual re-

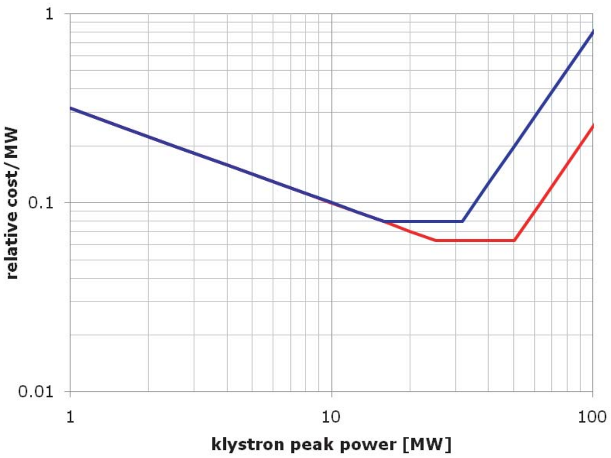

Figure 3: Empirical estimation of the relative cost function of klystrons per MW of power output [7]. The blue line presents the present state of the art, while the red line that extends the blue line to lower relative cost at high peak power assumes a major development investment.

gulation is controlled by the LLRF system. In addition an individual regulation on a μs time scale of RF power amplitude and phase to each cavity is required, fast enough to respond to changes within the RF pulse. This requires the introduction of a fast vector modulator which is also controlled by the LLRF system.

The klystron RF power amplifiers are a major cost driver. At high power levels their cost increases with the square of the output power as shown in figure 3 which is based on an empirical estimate [7]. The present cost optimum seems to be around klystron output power of 10 to 15 MW. Therefore cost efficiency of around 15% can be gained if a single klystron can be used to power multiple cavities, even though such a distribution is more complex [8]. For a total of 100 elliptical cavities and a further 50 spoke cavities, this amounts to a considerable investment cost reduction. The concept of multiple cavities per klystron will make the RF distribution more complex as it requires the introduction of mechanical phase shifters and fast vector modulators for individual regulation of the RF power level and phase shift to each cavity. Note that in all cases a power overhead of roughly 30% should be included in the available klystron output power for an optimal regulation by the LLRF system of the cavity power level and phase [14].

As the low-β cavities need less RF input power, as explained in section 4 below, an option is to investigate the use of other RF amplifiers such as inductive output tubes (IOT). They have a lower amplification factor than klystrons, but a higher efficiency. Cost savings for a solution with IOTs instead of klystrons could be in the same order as for a solution with 4 cavities per klystron [8].

Besides the RF power amplifier, also the high voltage power supply and pulse modulator are an issue. Conventional pulse modulators require an important amount of installation space. Solid-state modulators are both smaller and more reliable. At present these modula-

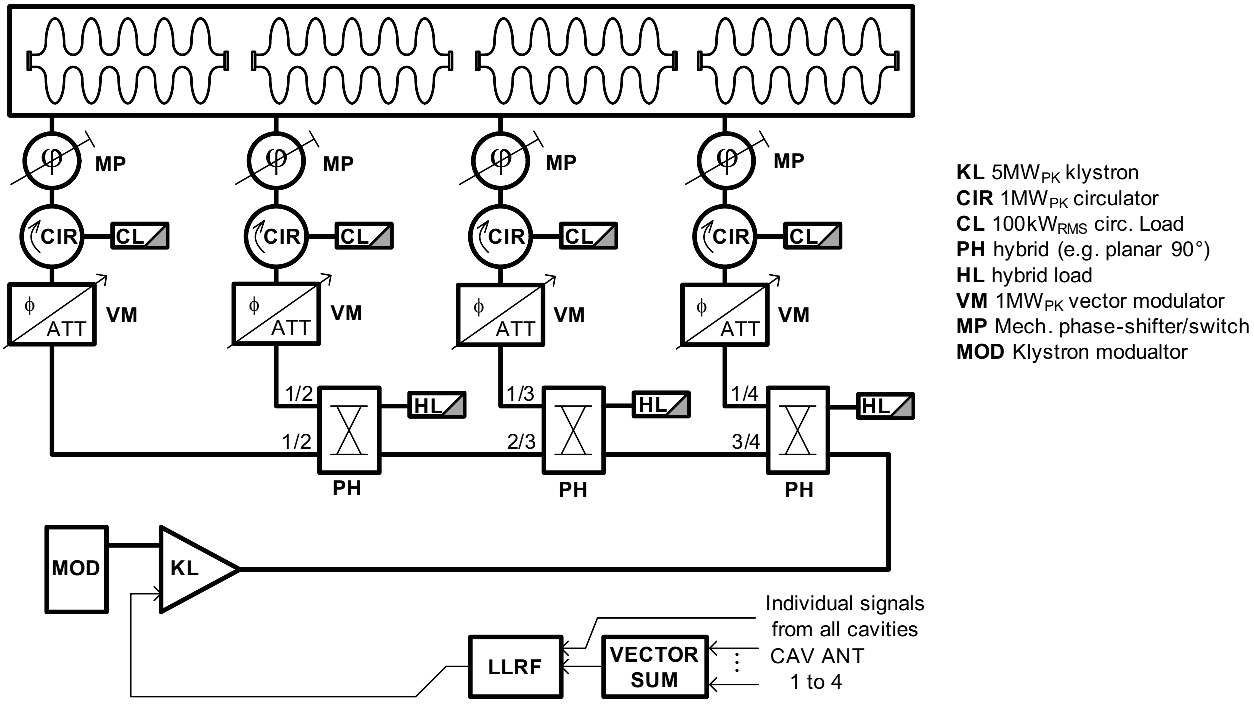

Figure 4: Layout of an RF distribution scheme where 1 klystron drives 4 cavities (courtesy D. Valuch) [8]. Hybrids are used for a linear power distribution among the cavities. Vector modulators do fast amplitude and phase control within a pulse. Mechanical phase shifters are used for initial phase regulation or isolation of a cavity.

Table 2: *Basic parameters of the ESS normal and superconducting cavities [1]*

Cavity	T [K]	E [MeV]	F [MHz]	β	l [m]	G [MV/m]
Source	300	0.075			2.5	
RFQ	300	3	352.2		4.0	
DTL	300	50	352.2		19.2	
SSR	4	80	352.2	0.35	23.3	
TSR	4	200	352.2	0.50	48.8	
Elliptical 1	2	660	704.4	0.65	61.7	15
Elliptical 2	2	2500	704.4	0.92	154.0	15

tors only supply short μs pulse lengths and development work is required to reach the longer ms ESS pulse length.

The main development programs and feasibility studies foreseen are therefore:

- low level RF signal generation and control of the RF power generation, RF power distribution and cavity tuners, see section 5.
- solid-state pulse modulator for the klystron power amplifier, see section 6.
- use of alternative RF power amplifiers for the low-β cavities, see section 6.
- input power coupler and higher order mode damping (output coupler), see section 7.
- fast high power RF vector modulator for the multiple cavities per klystron RF power distribution concept, see section 7.

4 The Superconducting Accelerating Cavities

RF acceleration is the most common method of acceleration used in high energy accelerators. DC acceleration is used in cathode ray tubes (CRT TV screens), X-ray tubes and tandem-van

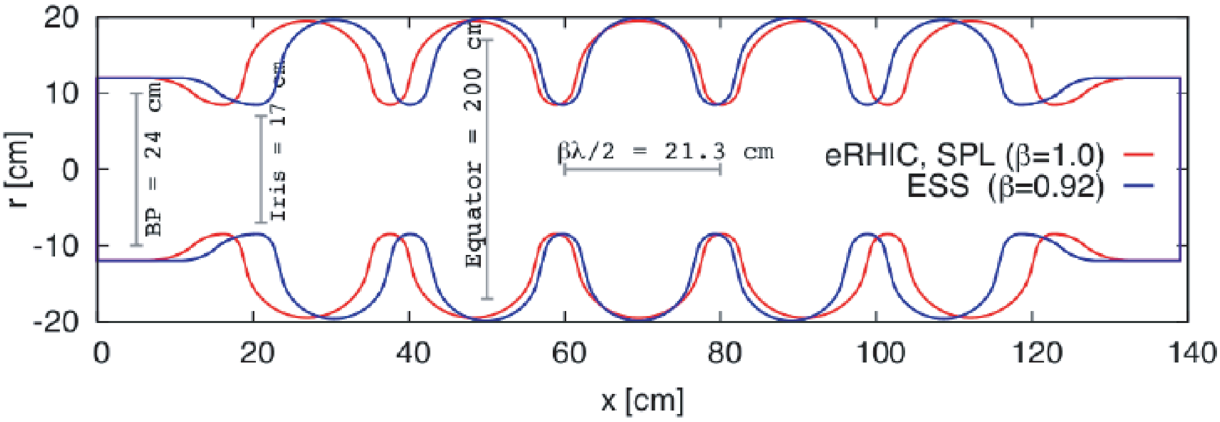

Figure 5: Layout of the superconducting 5 cell elliptical cavity type 2 ($\beta = 0.92$) in comparison with the $\beta = 1$ SPL cavity [1].

der Graaff accelerators, all below 25 MeV. In linear accelerators, RF acceleration is normally done in pulsed mode while synchrotron accelerators typically use constant wave (CW) mode. The design of RF accelerating cavities is further determined by a choice of travelling wave or standing wave operation. Each cavity can have one or multiple cells in which the RF wave resonates. The length of each cell is defined by the RF phase advance per cell. The aperture of the cell is important for the cavity RF filling time and the impedance seen by the beam. By habit, superconducting cavities are mostly designed for standing wave operation. Several such cavities are assembled together in one cryostat which is then called a cryo-module.

The ESS superconducting elliptical cavities are designed for pulsed power operation and a standing wave at 704.4 MHz. The basic parameters of the cavities are listed in table 2. Only the two families of elliptical cavities concern our development work as they are operated at 704 MHz. These cavities are assembled in two families of cryo-modules:

- $\beta = 0.65$ cryo-module with 6 superconducting 5-cell cavities and 4 (superconducting) quadrupoles, 11.45 m long.
- $\beta = 0.92$ cryo-module with 8 superconducting 5-cell cavities and 2 (superconducting) quadrupoles, 14.26 m long.

Figure 5 shows the layout of a 5-cell $\beta = 0.92$ elliptical cavity in comparison with a $\beta = 1$ cavity for the SPL and eRHIC (Brookhaven National Laboratory, 703.8 MHz operation). The similarity in their design is clearly visible: the $\beta = 0.92$ cavity is slightly compressed with regard to the $\beta = 1$ cavity. A collaboration between the ESS, SPL and eRHIC will develop a standard cryo-module to be used for all three projects. The distance between the cavities inside the cryo-module has to be carefully studied to suppress cross talk between neighbouring cavities. There is one RF input power coupler per cavity to deliver 1 MW peak power at a 4% duty cycle. The achievable accelerating gradient will decrease in inverse proportion to the beam current, thus an upgrade of ESS to a higher beam current and power will require extra accelerating cavities to be installed.

5 The Low Level RF Signal Generation

The low level RF (LLRF) generates a low power level RF signal for the klystron RF power amplifier. This RF signal is regulated by feedback loops from the cavity RF input and by feedforward loops based on known klystron and cavity behaviour in relation to Lorenz detuning of the cavity by the high power RF pulses and the accelerator beam pulses. The LLRF must be fast enough to correct the shape of its RF signal output within a single pulse. In addition the LLRF controls the mechanical cavity tuner that ensures that the cavity resonance frequency will match the desired operation frequency [16]. The schematic layout of such a control system using digital feedback only is shown in figure 6. A combination of digital and analogue feedback will be required for high frequency signals [17]. The stability requirements have to be investigated, but might be in the range of 0.01 to 1% in amplitude and 0.01 to 1° in phase of the accelerating field [15]. For the multiple cavities per klystron concept, the LLRF needs to determine the average power level and phase advance of all connected cavities to regulate the klystron output power level and phase. Simultaneously the LLRF then also regulates the individual power attenuation and phase shift for each cavity through a fast vector modulator.

There is a difference between LLRF requirements for linear and circular accelerators at low RF frequencies and high RF frequencies. In a circular accelerator, normally there is a constant beam loading of the accelerating cavities, although some of the buckets in the bunch train of particles might be empty: the RF is operated in constant wave (CW) mode. A linear accelerator on the other hand is normally working in pulsed mode, thus the LLRF has to correct for Lorenz detuning. For low frequency circular accelerators, say below some 100 MHz, the required signal processing speed is relatively low and fully digital signal processing is possible. At higher operation frequencies, partly analogue systems are obligatory due to the high processing speed required.

The LLRF development contains the following steps:

- design model study. A software model has to be developed of the RF system to study its behaviour and determine the requirements for hardware and software [18].
- RF signal generation and monitoring hardware, including analogue RF, digital signal processing and processors (complex programmable logical device, CPLD, and field-programmable gate array, FPGA) for the feedback and feedforward loops. This can be grouped in different blocks:
  - conditioning logics
  - modulator high voltage switch and limit
  - tuner loop
  - RF modulator and feedback
  - high power modulation for individual cavities

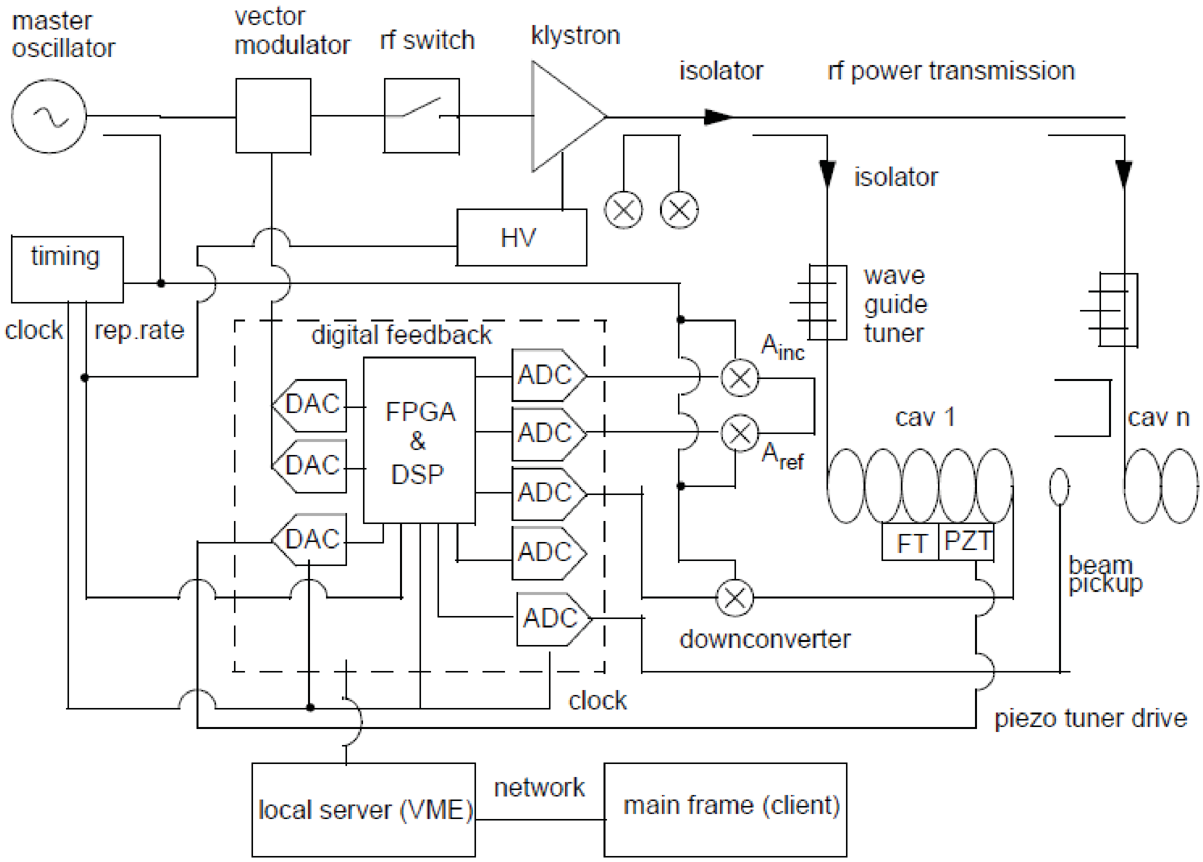

Figure 6: Design layout of a low level RF control system using digital feedback only [15].

The hardware can be based on hardware developed for other accelerators. A detailed study is required to see which existing hardware would suit best. Modifications for a multiple cavity per klystron concept are required.

- software programs for the above mentioned hardware

Due to the specific requests, especially the speed, for the LLRF control it consists of custom built hardware. Different concepts exist for almost any existing accelerator, developed in-house by their institutes. Each solution has different levels of complexity according to the requirements of the accelerator. Some of these existing hardware concepts might be well suited for the ESS accelerator and can possibly be adapted with minor modifications. It is therefore worthwhile to investigate the different systems in use at existing accelerators, especially at similar accelerators to ESS like the CERN Linac 4 and SPL [17] or the SNS at Oak Ridge and others [19]. The advantages and disadvantages of these concepts have to be studied to determine which of these implementations is best suited to copy (wholy or partly) to the ESS. Due to the multiple cavities per klystron concept, parts must be modified according the layout that will be chosen for the high power RF distribution system.

An extensive listing of existing LLRF systems is given in [15], here we list only a few of them:

- LHC [20, 21]: also to be used for Linac 4. Tested and supported by CERN's RF group. VME based, but requires a special VME crate with modified backplane (16 bits) and an extended (non-standard) depth. Some initial problems appeared with the custom built power supply.
- LEAR [22]: also to be used for Booster and PS. Tested and supported by CERN's RF group. Uses VME64x standard.
- FLASH: includes control of the cavity's piezo tuner [16]. Developments are ongoing to adapt it for XFEL [23, 24] and ILC [25].
- SPIRAL [26]: an upgrade is being studied in which the CERN LEAR hardware platform is being considered.
- SNS [27, 28]: accelerator with a design and functionality similar to ESS.

6 The RF Power Generation

The high power RF system amplifies the low power level RF signal from the LLRF and distributes it to the accelerating cavities. The power generation part consists of an RF power amplifier, its high voltage power supply and pulse modulator. The high power RF distribution network is described in section 7 below.

For high energy particle accelerators the common RF power amplifier is the klystron. In its simplest form it is based on a vacuum tube with an electron source and collector and in between an input cavity, a drift tube and an output cavity. The klystron is a narrow-band, tuned amplifier with large amplification factors in the order of tens to hundred dB. It is used in frequency ranges of a few hundred MHz up to several GHz and is capable of delivering a power output of over a hundred MW. Klystrons, their high voltage power supplies and high power pulse modulator are all commercially available. For the low-β cavities that require less power, a possible option is the use of magnetrons, gyroklystrons (gyrotron), inductive output tubes (IOT) or solid-state amplifiers (for a short comparison see e.g. [29, 30]).

The topology of the pulse modulator that generates the high voltage pulse for the klystron amplifier is shown in figure 7. The Uppsala based company ScandiNova develops solid-state based compact modulators [31]. These modern technology modulators are smaller, have a higher reliability and life time and will therefore be more cost effective in operation and maintenance than traditional modulators based on thyratrons. Due to the solid-state technology they are more flexible in varying the output pulse length and have a better pulse shape quality (less voltage droop) than traditional modulators. They might also be more flexible in case of an upgrade to higher repetition rate. Some of ScandiNova's modulators have been recently acquired by CEA Saclay, France, and PSI, Switzerland, for 12 GHz klystrons. However development work is required to make their modulators compatible to the long pulse length required by ESS. A related development is to investigate if one modulator can serve multiple klystrons.

Elements and development aspects of the RF power generation system are:

- klystron tube: commercially available, but a prototype is to be ordered and tested. About 30% spare power required for LLRF regulation.

  Companies: CPI (US, used by CERN and CEA Saclay) [32], Thales (France, no 704.4 MHz klystron yet) [33], Toshiba (Japan) [34].

- high voltage power supply and pulse modulator: commercially available, but a prototype is to be ordered and tested. Development work is required to make modern solid-state modulator compatible to the ESS pulse length.

  Companies: ScandiNova Systems AB, Uppsala [31].

7 The RF Power Distribution

The RF power distribution system consists of waveguides, circulators, loads and couplers as shown in figure 2. As the cavity is only matched to the klystron output when fully filled and with beam inside, there will be a reflection of its input power when the RF pulse starts. The circulator passes the klystron power straight to the cavity but returns the reflected power from the cavities to the load attached at its third arm in order to protect the klystron from damage by the reflected power. A set of waveguides transports the RF power from the klystron, in a gallery or side tunnel, to the accelerator tunnel. Different design options of

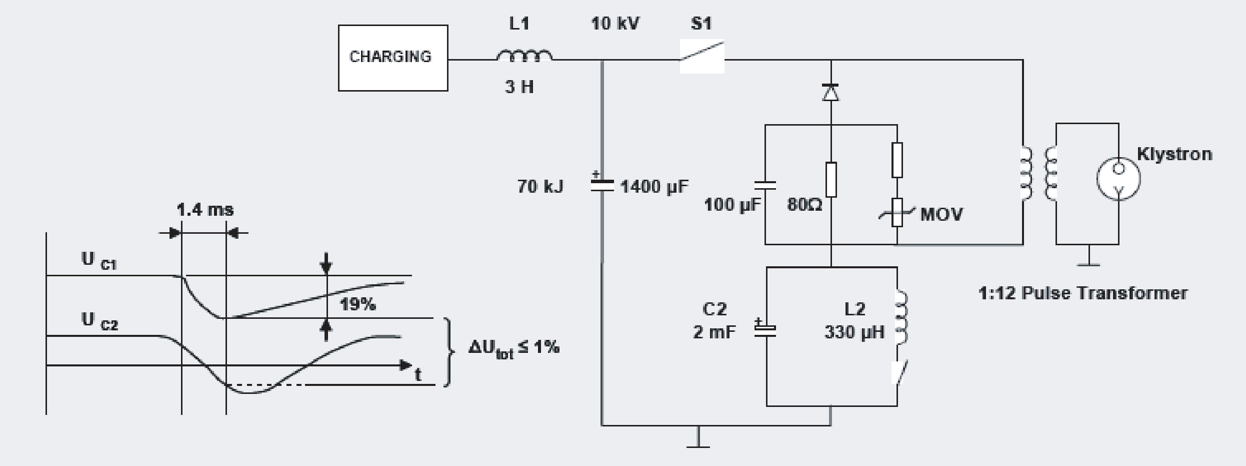

Figure 7: Topology of a klystron modulator (courtesy ILC) [7].

the waveguides are to be foreseen to adapt to needs along the transport line and to minimize the radiation that penetrates from the accelerator into the gallery.

The input power coupler transfers the RF power into the cavity (and the beam). It has to provide a match between the impedance of the klystron and waveguides with the impedance of the cavity and beam, to avoid power reflections [11]. The power coupler also has to withstand the full RF peak power while not heating the cavity and its cryostat. The peak power limit of the coupler will determine the accelerating gradient that can be reached in the cavity under full beam loading. Thus a higher power coupling will enhance the efficiency of the cavity and the accelerator, see section 2. Power couplers can be of a coaxial or waveguide design [13]. The coupler also contains a RF vacuum window that separates the cavity vacuum from the waveguide and has to withstand the full RF power load. Due to the long lengths, the waveguides might be filled with dry air instead of being under vacuum.

The travelling charges of the accelerated beam cause a wakefield in the cavity. A beam pulse is divided in bunches at distances that match the RF acceleration frequency. However, bunch phase noise and charge jitter as well as an offset of the beam from the cavity centre creates a wide spectrum of higher order mode (HOM) frequencies that change the cavity impedance and cause beam instabilities. Simulations have been done for both the SNS superconducting linac [35] and the SPL [36]. It was found that HOMs causing beam scatter or even beam loss cannot be excluded. It is therefore important to either damp or extract the HOM frequencies. This can be done by inserting absorber material or installing a HOM output coupler. The HOM output couplers reject the fundamental mode frequency but pass the HOM frequencies which are then coupled out to an external load. The HOM couplers can be of a coaxial type, which are susceptible to multipacting[1], or waveguide couplers which are natural high pass filters but bulkier and therefore can have a considerable cost impact. Most accelerators with superconducting RF cavities like FLASH, SNS and CEBAF, have installed HOM coaxial couplers. Tests have shown that the coaxial coupler antenna should be superconducting to prevent excessive heat load into the cavity [37].

A major development effort is the question regarding RF power distribution from a single klystron to multiple cavities: if this is possible and if such a system is economically more efficient than a one cavity per klystron model. This requires the introduction of fast vector modulators for individual regulation of the RF power level and phase shift to each cavity. The vector modulator must be fast enough the regulate the power level and phase within the ms RF pulse length and at a peak power up to 1 MW. The response speed, range and other parameters of the vector modulator have to be determined by the design model study

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[1] multiple impact electron amplification

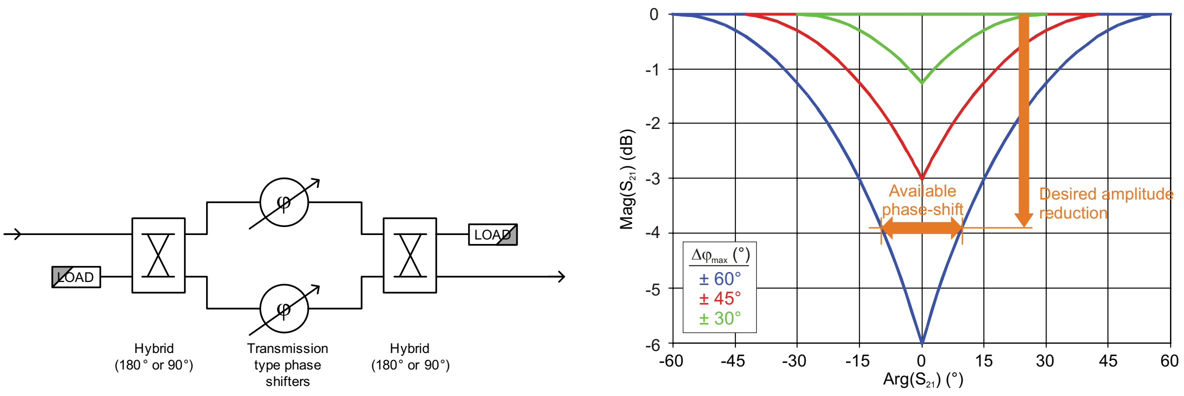

Figure 8: Schematic layout of a vector modulator (left) and its range of operation [8].

described in section 5. The schematic layout of such a vector modulator is shown in figure 8. It consists of six components. The phase shifters might be made of ferrite materials, so a study has to be done for a search of the optimal material to be used. Both CERN [38, 39] and Fermilab [40, 41] have done research in this area and came up with solutions, but unfortunately for different RF frequencies of 352.2 MHz and 325 MHz respectively and at power levels below the 1 MW required for the ESS. Therefore a considerable development effort is to be foreseen for the vector modulator.

Elements and development aspects of the high power RF distribution are:

- fast vector modulator and multiple cavities per klystron concept: A software model has to be developed of the RF system, in coordination with the LLRF software model, to study behaviour of the vector modulators and to determine their requirements. A study has to be performed for the optimal ferrite material to be used in the vector modulator. Stability and power level are crucial questions [42, 43].
- input power coupler: CEA Saclay is developing a 1 MW type (test limit from klystron power) [44]. A development to increase the power level will gain the ESS as an upgrade to higher beam power will require less extra accelerating structures.
- higher order mode (HOM) output coupler: to extract the higher order modes. To be connected to a load. The expected power is less than 1 kW or 0.1% of the power coupler capacity [45].
- waveguides: commercially available, but different design options adapted to location specific demands (e.g. gallery to accelerator tunnel feed through).
- circulator: commercially available, but a prototype is to be ordered and tested.
- high power load: commercially available, but a prototype is to be ordered and tested.
- directional coupler for power measurement on wave guides: commercially available, but a prototype is to be ordered and tested.

Due to the relative long RF pulse length no RF pulse compressors are needed.

8 The RF Test Facility

A reliable development of the RF system components and the multiple cavities per klystron concept requires that all components and the complete system are tested in a realistic environment. Thus an RF test facility is required where a complete RF system can be connected to cavities and tested, albeit without beam. The connection to superconducting cavities is the only way to simulate the fast detuning on μs level due to RF power pulsing. Mechanical detuning due to e.g. temperature differences is expected to be on a time scale longer than the ms RF pulse length. To test the multiple cavities per klystron concept it should be sufficient to connect just two cavities to a single klystron, but the option should be kept open to test with more cavities connected.

Few RF test facilities exist in Europe with the option to connect and test superconducting cavities:

- BESSY (HoBiCaT) [46], equipped for 1300 MHz.
- CEA Saclay (CryHoLab) [47], equipped for 352 and 704 MHz.

- CERN, equipped for 352 and 400 MHz with an extension to 704 MHz planned.

- DESY [48], equipped for 1300 MHz.

Thus only the CEA Saclay test stand is presently equipped for 704 MHz required for the ESS development effort.

The basic layout of the RF test facility as used for component testing and initial development is shown in figure 9. The klystron is connected to a single superconducting cavity for the first development phase of the fast vector modulator. In later stages a second cavity and vector modulator would be connected in the second waveguide line instead of the load shown in the figure. The test facility would then be rearranged according to the layout shown in figure 4 but with only two cavities connected: the two left most. The resulting layout is shown in figure 10. Different layout options are required for the sequential stages of its construction and commissioning including acceptance testing of prototype components. It is a multi-functional test facility focused on the development of the multiple cavities per klystron concept. It could have either vertical or horizontal cryostats to house the superconducting cavities. A vertical cryostat has a simpler design than a horizontal cryostat, but requires a test hall with a free space under the gantry at least twice the height of the cryostat (to install the cavity). Vertical cryostats are common for the acceptance testing of cavities and thermometry studies. On the other hand, mechanical cavity tuners are normaly designed for horizontal cryostats, but there is no principal problem designing one for a vertical cryostat [44].

The development process of the RF system and the construction of the RF test facility will run in parallel. Development and test of prototype components can be adapted to the moment where they are required to appear in the test facility. The build-up of the RF test facility can thus follow the line of the RF development studies. It would start with

- high voltage pulse modulator (pulse shaping).

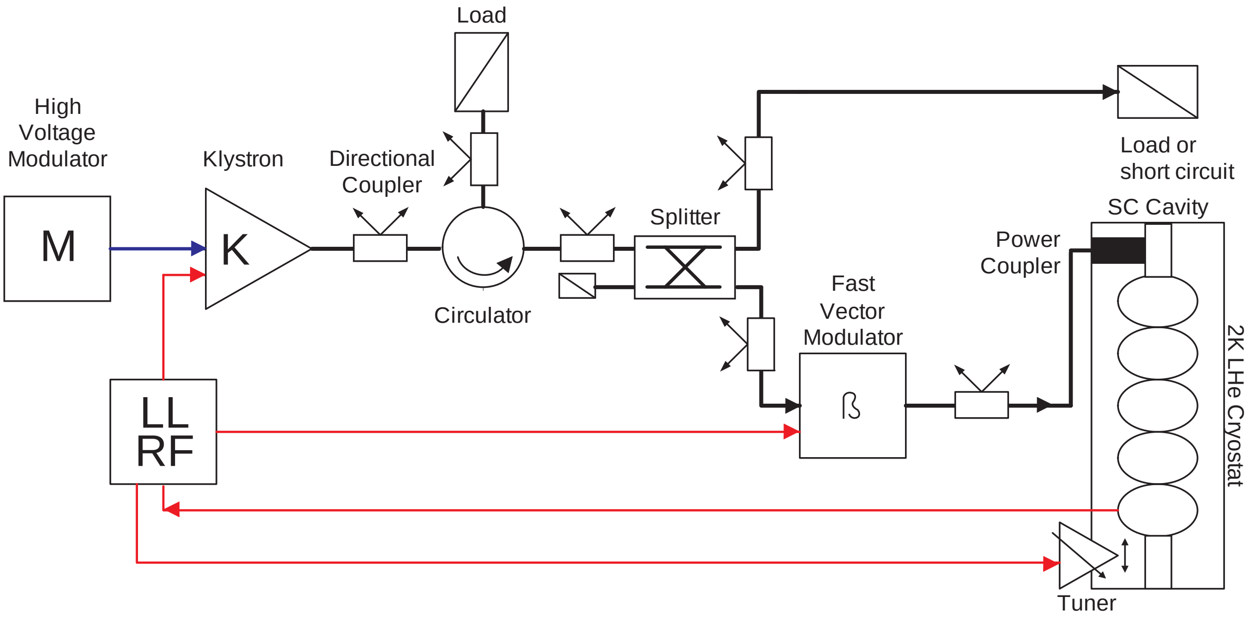

Figure 9: Configuration option of the RF test facility in which the two waveguide lines after the hybrid splitter are connected to a load and a superconducting cavity. This option is useful during initial component testing and development of the fast vector modulator.

- klystron (tuning, linearity, bandwidth, efficiency).
- circulator and load.
- high power RF vector modulator.
- “warm” tests on power input coupler and HOM output coupler.

Then when superconducting cavities and their test cryostats are available, the development work can continue with

- power input coupler (cold test).
- HOM output coupler (cold test).
- low level RF control system.
- multiple cavities per klystron concept.

All of these components are an integral part of the RF system and prototypes must be ordered and tested before series production can commence for the ESS installation. Simultaneously it will create a complete RF test facility to validate the multiple cavities per klystron concept.

9 Conclusions

The main development issues for the ESS RF system have been described. The work is supposed to focus on the

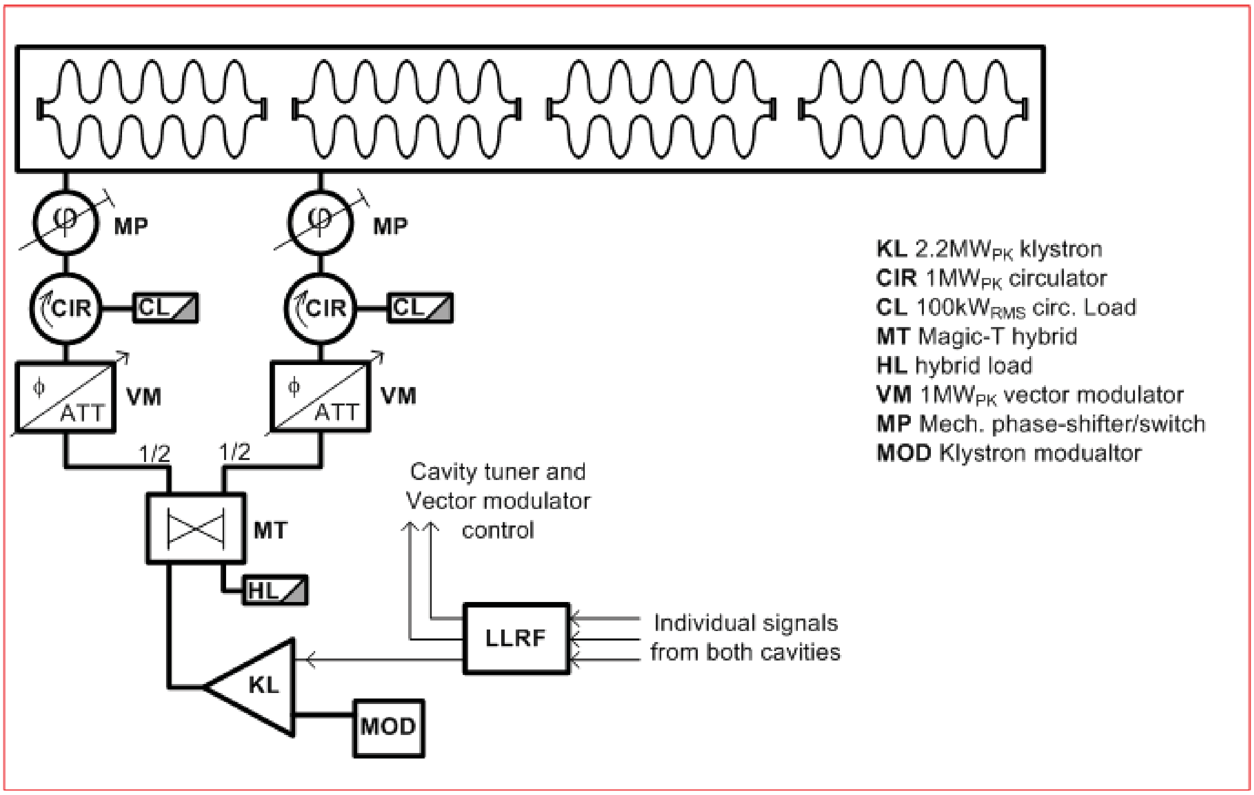

Figure 10: Layout of an RF distribution scheme where 1 klystron drives 2 cavities (courtesy D. Valuch) [8].

- low level RF signal generation and control of the RF power generation, RF power distribution and cavity tuners,
- solid-state pulse modulator for the klystron power amplifier,
- use of alternative RF power amplifiers for the low-β cavities,
- input power coupler and higher order mode damping (output coupler),
- fast high power RF vector modulator for the multiple cavities per klystron RF power distribution concept.

In addition commercial components for the RF power distribution system have to be tested.

In order to address these development issues we need to launch a study to investigate the feasibility and stability of the RF system under operation with multiple cavities per klystron and contrast the cost and operational performance of this option to that of other alternatives, for example instead of a klystron to drive multiple cavities, to use a single inductive output tube (IOT) to drive a single cavity. In parallel we need to develop or identify suppliers for RF components and build a test-stand to first validate the performance of components, such as vector modulators, and later also of system aspects, such as actually operating multiple cavities per klystron and the associated specialized LLRF system. Some aspects can be tested at low power, but especially the system aspect can only be determined at high power. Moreover, reaching the design performance of power RF components often depends on following a proper conditioning procedure where the parts are subjected to increasing levels of RF power to increase their tolerance level to high field levels. This requires a high-power test facility which we foresee to be gradually assembled as the development process advances, but it will also be under constant reconstruction in order to test components and concepts under different conditions.

Extensive testing of the accelerating cavities and their cryostats is not part of the RF development test program. In the development phase we would expect to receive already tested prototype cavities from other institutes. Fabrication of prototype cavities are being discussed under the EuCARD FP7 framework (WP10) and the SPL study. In the build-up phase of the ESS the test facility could be used for acceptance testing of production cavities.

The ESS proton linac conceptual design report is foreseen for 2012. Thus, before then the development work must show which options are feasible. This is only possible if the build-up of the RF test facility starts during 2010 because this leaves only less than two years to complete the development work and associated testing. There exist other RF test facilities in Europe at BESSY, CEA Saclay, CERN and DESY, but these are focused on the development of the X-FEL and SPL and can thus not give unlimited access for ESS development work. Due to its proximity to ScandiNova, Uppsala University is in a perfect location to support the development of the modulator. Uppsala University is prepared to take the lead in the development of the ESS RF system. This development work will include, as a natural part, prototype testing of klystron, circulator and load. As long term operation under realistic conditions is a natural part of the testing, the basis of an RF development test facility is founded this way, and therefore Uppsala University is the perfect location for the RF development test facility.

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