THE RF POWER SOURCE FOR THE HIGH BETA ELLIPTICAL CAVITIES OF THE ESS LINAC

K. Rathsman, H. Danared, R. Zeng, ESS, Lund, Sweden
R.J.M.Y. Ruber, Uppsala University, Sweden; C.A. Martins, Laval University, Canada
C. Lingwood, Lancaster University, UK; A.J. Johansson, Lund University, Sweden

Abstract

The European Spallation Source (ESS) is an intergovernmental project building a multidisciplinary research laboratory based upon the worlds most powerful neutron source. The main facility will be built in Lund, Sweden. Construction is expected to start around 2013 and the first neutrons will be produced in 2019. The ESS linac will deliver 5 MW of power to the target at 2.5 GeV, with a nominal current of 50 mA. The 120 high beta elliptical cavities, which operate at a frequency of 704 MHz and accelerate protons from 600 MeV to 2.5 GeV, account for more than half of the total number of RF cavities in the ESS linac and three quarters of the total beam power needed. Because of the large number of RF power sources and the high power level needed, all the design and development efforts for the RF power source have so far been focused on this part of the accelerator. The design and development status of the RF power source is reported in this paper with emphasis on reliability, maintainability, safety, power efficiency, investment cost and production capacity.

INTRODUCTION

The ESS linac [1] will accelerate 50 mA of protons to 2.5 GeV in 2.86 ms long pulses at a repetition rate of 14 Hz. This produces a beam with 5 MW average power and 125 MW peak power.

The RF Power Scheme

The layout of the ESS Linac is presented in Ref. [2]. The accelerating structures consist of one RFQ, 3 DTL modules, 28 superconducting spoke resonators, 64 low β and 120 high β superconducting elliptical cavities. Two RF frequencies will be used for acceleration, 704.42 MHz for elliptical cavities and 352.21 MHz for spoke resonators and the normal conducting structures.

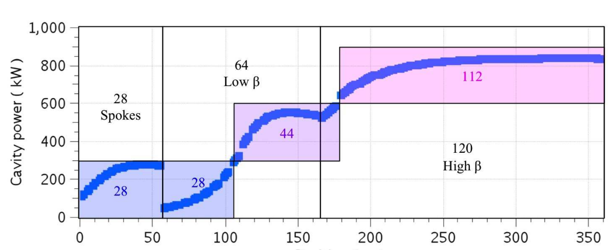

Figure 1: The supply of RF to each of the superconducting cavities in the Linac based on the hybrid layout presented in [3].

Table 1: Specified Output Power for the RF Power Sources

No. of Units	Type	Frequency (MHz)	Power (MW)
6	Klystron	352	1.3
28	IOT	352	0.5
28	IOT	704	0.5
44	Klystron	704	1
112	Klystron	704	1.5

The cavity power in the superconducting part of the ESS Linac is shown in Fig. 1. In order to dimension the RF power source with only a handful of different systems we have divided the RF power levels into three categories. IOTs and/or solid state amplifiers are the natural choice for low power range (0-300 kW), while two kind of klystrons and modulators will be used for medium (300-600 kW) and high (600-900 kW) power levels. The corresponding power specifications for the RF power source are listed in Table 1, where a scaling factor of 5/3 with respect to the required input power is used that has been derived from power calculations (below).

In addition, the normal conducting part of the Linac will be supplied by a total of six klystrons with an output RF power of 1.3 MW, one for each of the RFQ and the first DTL module and two for each of the second and third DTL modules, as shown in Fig. 2. This layout differs from the power scheme of the Linac4 design, which includes both 1.3 MW and 2.5 MW klystrons [4].

As a conclusion, ESS will have 5 different RF power systems for acceleration including two different systems of IOTs and/or solid state amplifiers and three families of klystrons supplied by two kind of modulators.

POWER CALCULATIONS

The high power 704 MHz RF power source is the most critical due to the high power and the large number of units needed. To dimension the klystron and modulator the amount of losses and safety margins needs to be taken into account. This is done by first of all calculating the expected power levels during nominal operation, and thereafter by adding a safety margin of 20%.

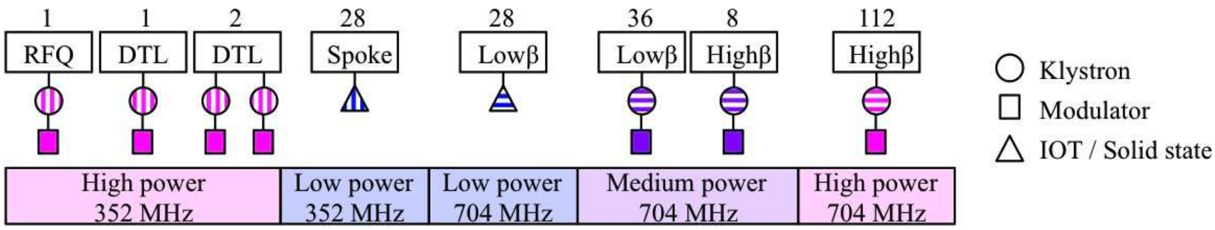

Figure 2: Layout of the RF power system for acceleration. Circles and squares represent klystrons respective modulators, while triangle represent IOT / Solid state amplifiers.

Nominal Values

The maximum RF power delivered to the high beta elliptical cavities is 0.9 MW. It is assumed that the coupler impedance is perfectly matched to the 50 mA beam load.

The power loss in the RF distribution system, i.e., RF wave guides, circulators, bends, flanges and bellows, is estimated to 5%. This might be an underestimate since we have not considered reflections due to mismatches. Nevertheless, the power loss due to mismatches is assumed to be small on an average.

In order to facilitate the control of the phase and the amplitude of the fields in the cavities, the klystrons are typically run far below saturation in a linear region of operation, which leads to a reduced power efficiency. Linearization techniques as well as the usage of piezo tuners are anticipated to avoid excess power margins [5]. To improve the performance of the LLRF system further the klystron modulator will have to generate a high quality pulse with a 99.98% pulse to pulse stability and low voltage ripple. The LLRF system cannot effectively compensate for high frequency (>1 kHz) noise with PI feedback controller, and the high frequency ripple in modulator shall therefore be well below 0.1% of the peak voltage. On the other hand, a low frequency (<100 Hz) variation and droop can be compensated, however at the cost of increased margin for regulation. Typically 2% additional power is required per 1% error in voltage and therefore the slow frequency variations shall be below 3% and preferably lower. Detailed information on the ESS klystron modulator is given in Ref. [6].

Taking into account the 5% power loss in the distribution system and a 20% margin for LLRF regulation, the required nominal peak power delivered by the klystron at saturation is given by

$$p_k = \frac{0.9\ \mathrm{MW}}{0.95 \times 0.8} = 1.2\ \mathrm{MW}$$

The klystron efficiency should be as high as possible, without affecting lifetime and stability of the klystron. With a perveance

$$K = 0.55\ \mu\mathrm{AV}^{-3/2}$$

a 65% efficiency is plausible. The nominal beam power, which has to be supplied by the modulator, is then given by

$$p_m = \frac{1.2\ \mathrm{MW}}{0.65} = 1.8\ \mathrm{MW}$$

The beam perveance then gives the required nominal cathode voltage U as

$$U = \left(\frac{p_m}{K}\right)^{2/5} = 102\ \mathrm{kV}$$

Specified Values

The RF power source will be optimized for the nominal values. However by dimensioning klystrons and modulators to deliver 20% extra power we will be able to increase the power if necessary. In addition the reliability improves. With the additional power margin the specified maximum output peak power by the klystron is 1.5 MW. The klystron modulator, in its turn, needs to supply a maximum of 2.3 MW in peak power, which corresponds to a cathode voltage of 113 kV.

RF Power Efficiency

The beam pulse repetition rate at ESS is 14 Hz with a beam pulse length of 2.86 ms, which corresponds to a beam duty factor of 4%.

For a modulator with a pulse transformer the expected rise time is 200 μs that together with 400 μs to fill the cavity result in a total pulse length of $\tau = 3.5$ ms. This corresponds to an RF duty factor equal to

$$D = 14\ \mathrm{Hz} \cdot 3.5\ \mathrm{ms} = 4.9\%$$

Therefore, the klystron modulator will be dimensioned for an average output power of

$$4.9\% \cdot 2.3\ \mathrm{MW} = 113\ \mathrm{kW}$$

Taking into account 90% power efficiency for the klystron modulator the nominal power consumption can be calculated as

$$4.9\% \cdot 1.8\ \mathrm{MW}/90\% = 100\ \mathrm{kW}$$

In relation to the RF power delivered to the power coupler

$$4\% \cdot 0.9\ \mathrm{MW} = 36\ \mathrm{kW}$$

we can estimate the power efficiency for the high beta elliptical section to be roughly 30% if we also take into account for example the klystron solenoid, water cooling system, power supplies, etc.

Since the high beta elliptical cavities accounts for roughly 75% of the total power delivered to the beam, we can expect a total power consumption of $5\ \mathrm{MW}/0.30 = 17\ \mathrm{MW}$. Then, with an annual operation of 5200 h the total power consumption is 87 GWh per year. This is almost a third of the total power budget for ESS, equivalent to an operation cost of roughly 5 MEUR.

CHALLENGES

Technical Challenges

To our knowledge, no one has achieved 3.5 ms long pulses at these power levels and repetition rates, and especially not for the amount of units as required for ESS. There is a risk that thermal stress, in terms of RF pulsed heating, will cause reliability issues of the RF Power source. The probability of arcs in the klystron and RF distribution system will also increase with the pulse length. The only conclusion at this point is that more analysis of the implication of these very long pulses are needed.

Sustainable Research Facility

The European Spallation Source is breaking the ground for a sustainable research facility [7]. Since the RF power source is the major consumer of electrical power at ESS and the major producer of surplus heat, the design of the RF power source and gallery is carried out together with a dedicated energy team in order to maximize the power efficiency of the of the RF power source and to recoverer the surplus heat for use in the district heating system. The challenge is to find the balance of how far the power efficiency and heat recovery can be pushed, before the reliability will be affected.

Financial and Commercial Challenges

The RF power source and distribution system make up for a substantial part of the total accelerator budget. There are few qualified suppliers worldwide, and even less within the ESS member countries. This makes production, testing and the process for inkind contributions challenging.

Assuming an aggressive production, testing and installation rate of one RF power source per week, the orders must be placed in 2014 in order to deliver the first neutrons by 2019. This will require early prototyping and contracting to multiple vendors.

For this reasons, it might be beneficial to increase the RF power to the cavities in order to reduce the total number of power sources. For example, if the power delivered to each of the cavities could be increased by 25% on an average, then the production time could be shortened by almost a year. However, splitting the power from one klystron into two cavities in the high beta elliptical section is not to recommend from this point of view since this will worsen the klystron efficiency substantially and adding complexity.

Another possibility would be to use one modulator to two klystrons. The feasibility of such a solution depends on the modulator topology. The disadvantage is that in case one modulator fails, then two cavities will not be in operation. Secondly, both klystrons will be powered the same, regardless of the RF power output needed, so this will increase the power consumption. Another argument is the issues with the 3.5 ms long pulses, which are likely to worsen if the power is doubled. Again, more investigations are needed.

Access and Serviceability

In the present lattice design there is 1.6 m average center to center distance between the cavities in the high beta elliptical section. Thus the design of the klystron gallery is critical, and double rows of klystrons and modulators are now envisaged.

Personal Safety

Personal safety issues include large stored energy, large amount of cooling water, large quantities of oil, radiation (neutrons, x rays and electromagnetism). Lifting and transport of heavy objects is another important safety issue.

Reliability

The RF power sources are expensive and complex with many components. With more than 200 RF power sources and an assumed MTBF of 4 years (or 20000 h) per unit, we can expect to do maintenance every week. Further, an assumed mean time between failures (MTBF) of 40000 h for a klystron implies that 20 klystrons on an average will fail each year.

To be concluded, accurate analysis and considerations of failure rates and repair times are absolute prerequisite for the ESS RF gallery design, taking into account the large magnitude and complexity. Further, the design must be based on well proven solutions only. However, the concept of supplying one cavity only from one RF source will provide us the flexibility to operate the facility without having all of the RF power sources in working conditions.

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