HIGH POWER RF SOURCES FOR THE ESS RF SYSTEMS

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Abstract

The RF systems for ESS will consist of around 150 high power RF sources and will deliver 125 MW peak power to the proton beam during the 2.86 ms pulse with an average power of 5 MW. The two RF frequencies, 352 and 704 MHz, the different power requirements along the linac and the sources currently available strongly influence the choice of RF technology. This talk will focus on the high power RF solutions for the main parts of the linac. We present an overview of the available technology along with the first test results of the main sources. Additionally, we will present the preliminary design of a new 1.2 MW multi-beam super power IOT being designed together with industry for the high beta section of the linac.

THE EUROPEAN SPALLATION SOURCE

The European Spallation Source, located in Lund, Sweden, has entered the construction phase of a project to construct the world's most powerful neutron source. The facility is based around a proton linac and will deliver its first neutrons in 2019 and is expected to be fully operational with 22 instruments by 2025.

The linac will accelerate the proton beam to 2 GeV with a peak beam current of 62.5 mA. The RF systems will be pulsed at 14 Hz and during each pulse will deliver a peak power to the beam of 125 MW. The linac is divided up into different sections with accelerating technologies to match the increasing beam energy. The main RF systems are Radio-Frequency-Quadropole (RFQ), Medium-Energy-Beam-Transport (MEBT), Drift-Tube-Linacs (DTL), Spoke Cavities (SPK), Medium-Beta (MB) and High-Beta Elliptical Cavities (HB).

The main power requirements are listed in Table 1.

Table 1: Beam Power Requirements for the Accelerating Sections

	Total Peak Beam Power (MW)	Number of RF Stations	Frequency (MHz)
RFQ	1.60*	1	352
DTL	11.0*	5	352
SPK	8.02	26	352
MB	21.9	36	704
HB	89.4	84	704
Totals	132	152	

*Note that for the RFQ and the DTL the RF power includes the power lost in the cavity.

In addition to the power required for the beam, the RF sources must be capable of being operated with sufficient overhead for the LLRF to maintain the correct cavity voltage and phase. The RF plan and design currently assume a power overhead of up to 25% for feedforward and feedback systems, to compensate for microphonics, Lorentz detuning, beam loading, power supply ripple etc. Additionally, 5% power loss is assumed for the RF distribution system including losses in the transmission lines, circulators and mismatches. Please refer to [1] for details of the design of the phase reference line.

THE HIGH POWER RF SOURCES

The power level and frequency restricts the high power RF sources available for each section of the linac and in addition each section will need drive amplifiers and for the medium energy beam transport (MEBT) section, three high power amplifiers required for the buncher cavities.

The solid state and tube based RF amplifiers will be placed in a surface building along the length of the underground tunnel which will house the accelerating structures and proton beam. The RF gallery is split up into sections, with each section typically offering access to eight cavities through a common, connecting shaft, which will house waveguides from up to eight amplifiers and contain the cabling required in the tunnel. Figure 1 shows a preliminary representative section showing the layout of klystrons, the RF distribution system, racks for controls and one modulator for up to 4 klystrons for the medium and high beta part of the linac. To minimise the floor space, the 704 MHz klystrons will be placed vertically.

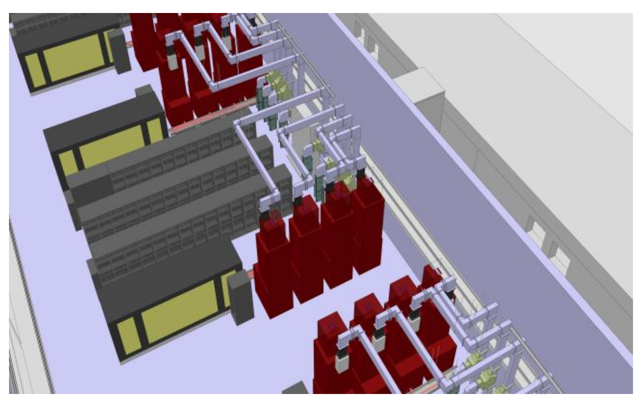

Figure 1: Preliminary typical layout in the RF gallery.

352 MHz, 2.8 MW Klystron

The RFQ and DTL sections of the linac each require high power klystrons with a peak power capability of 2.1 MW and 2.9 MW respectively including overhead and transmission losses. At this power level and frequency the klystron also intended for Linac 4 at CERN [2, 3] provides a good match. Currently no other sources have been identified which can match the power, efficiency and reliability of klystrons. The klystron has a diode gun and hence fixed perveance. The current baseline is to use a single 600 kVA (unitary power factor) modulator to feed two klystrons in parallel. This works well for the last four DTL tanks but since the first DTL tank and the RFQ will share the same modulator, the difference in power requirements mean that ideally the two klystrons should be operated with different cathode potentials. Operating the RFQ klystron at higher than required voltage for the RF output reduces the efficiency at the point of operation. Were it possible to reduce the voltage and hence the beam current, the expected lifetime of the klystron would be prolonged. Therefore under consideration is the possibility to operate the RFQ and the first DTL klystron from individual modulators. In addition to improving the efficiency and the life expectancy of the klystron, such a configuration would also have advantages in terms of redundancy in case of problems with one of the modulators. See Table 2 for the key requirements of the klystron.

352 MHz, 400 kW Tetrode Amplifier

The spoke section of the linac contains 36 spoke cavities. The main specifications of the RF parameters are given in Table 2. At this frequency and power level, considering available technology, reliability and efficiency, to achieve 400 kW, ESS has based the design on an amplifier consisting of two 200 kW tetrodes of a common high voltage supply, with the RF output of each tetrode combined using a 3 dB hybrid combiner [4]. Although the gain of tetrodes is low compared to other technologies such as klystrons and IOTs, with a pessimistic gain of 13 dB, each tetrode requires 10 kW of drive, which can be achieved with modern solid state amplifiers. Other options, for example to make use of a third tetrode, operated off the same high voltage supply, are also under consideration to reduce the overall size and cost of the drivers.

ESS currently expects to operate the tetrodes in Class B, so to reduce the quiescent current between pulses, the control grid will be modulated.

Figure 2 shows measured data of a single tetrode under test. It also shows that the anode efficiency at the point of operation is high, above 65%, even when operated below nominal power, as required for the regulation overhead, whereas in the case of operation with klystrons, this immediately reduces the overall efficiency at the point of operation. Even taking into account losses associated with the combining of two tetrodes, the lower expected life of a tetrode and the additional auxiliary systems, the tetrode solution remains attractive.

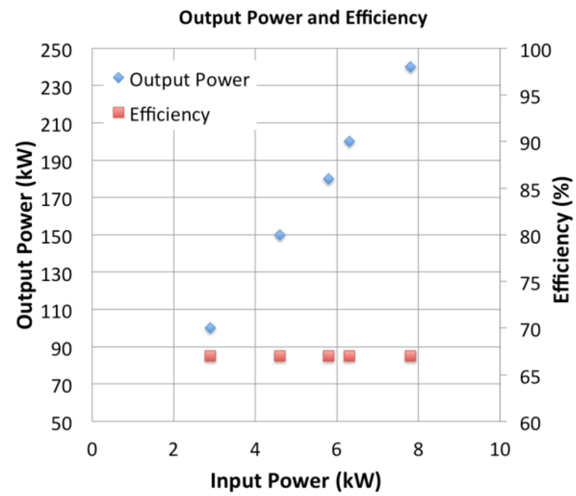

Figure 2: Measured data of a single tetrode under test. At 200 kW the anode voltage was 16 kV, screen grid and control grid voltages were 900 and -200 V respectively and the anode current was 18.7 A.

704 MHz, 1.5 MW Klystron

The Medium Beta section of the ESS linac includes 36 elliptical superconductive cavities to be supplied with RF power at 704.42 MHz. The required peak power-to-beam requirements vary from 210 to 870 kW, depending on the location of the cavity, plus a margin for RF regulation and losses in the distribution system. The high beta section, also operating at 704.42 MHz will be the longest part of the linac, and consists of 84 cavities, with input power levels varying from 836 to 1100 kW, plus the usual margin for RF regulation and distribution losses. A single RF source per cavity is required for LLRF control. ESS plans to use klystrons for the Medium Beta section, and superpower multi-beam IOTs for the High Beta linac. However, the 704 MHz, 1.5 MW klystron for the MB section serves as a technology backup for the HB linac, were the superpower IOTs to be unavailable at the relevant time. The main klystron requirements are shown in Table 2. The klystrons will be operated vertically due to the limited space available in the RF gallery.

A minimum efficiency is specified at saturation at nominal power but higher efficiencies are expected. The maximum high voltage required to achieve 1.5 MW RF output power is 115 kV, however since ESS will be operating up to four klystrons in parallel of a common HV supply, it shall be possible to operate the klystron at 115 kV, provided that the nominal RF output power is not exceeded. This applies even when the nominal power can be achieved at lower voltages but is necessary to compensate for variations in perveance between adjacent tubes.

Since most of the MB klystrons will be operating at reduced output power, ESS plans to operate some of the tubes at reduced cathode voltage in order to keep the

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efficiency as high as possible. Such operation is also expected to result in improved reliability and lifetime.

A klystron with parameters very similar to the ESS requirements has been developed by Thales for the Superconducting Proton Linac study at CERN. This tube operates horizontally with pulse length of 2 ms at 50 Hz repetition rate, but it could be adapted to the ESS requirements with some minor modifications. Tests were performed in the spring of 2014 and a peak power of 1.56 MW at 50 Hz was demonstrated, with a pulse length of 1.7 ms and > 65% efficiency at saturation.

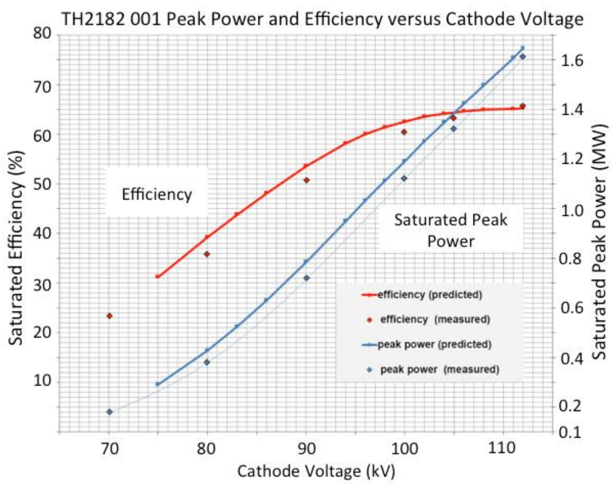

Figure 3: Saturated power and efficiency at saturated power as a function of high voltage. Note: This data was measured to satisfy CERN SPL parameters at 1.7 ms and a repetition rate of 50 Hz. The data is supplied courtesy of CERN and Thales Electron Devices.

Although these measurements are specific to the requirements of the SPL at CERN, the results give a good indication of the theoretically achievable parameters for ESS at 14 Hz and for pulse widths up to 4 ms.

704 MHz, 1.2 MW IOT

The final accelerating section of the linac, the high beta linac, consists of 84 RF sources each with an average peak-power-to-beam requirement in excess of 1 MW plus overhead and a margin for losses in the distribution system. This means that at full power operation approximately 80% of the ESS RF power requirement comes from the high beta linac.

Historically, the klystron has been the preferred amplifier technology, and in many cases, the only choice for high power RF production. However technical improvements in solid-state drivers and manufacturing technology have enabled IOTs (inductive output tubes) to be develop for the broadcast industry, where klystrons are now virtually obsolete.

The overall efficiency of klystrons at the predicted operation point is significantly lower than the efficiency, which can be achieved at saturation. The IOT, on the contrary, can have a higher maximum efficiency, however, importantly like the tetrode, the IOT does not saturate like the klystron. It can be operated close to the point of maximum efficiency whilst at the same time, maintain sufficient power overhead for regulation purposes.

Originally the construction and installation schedule of ESS, required the medium beta and high beta linacs to be completed at the same time, which did not leave sufficient time to develop separate klystrons for the medium and high beta linacs. Recently, however, a split installation schedule requires the medium beta klystrons to be operational in 2019, but the high beta linac comes later. Following a review of possible technologies, ESS has engaged in a programme with established tube amplifier manufacturers, to fund the development of a 1.2 MW multi-beam IOT. Following the factory acceptance, the IOTs will be tested in a test stand at CERN currently under construction. If successful, use of such IOTs instead of klystrons for the HB part of the linac, is estimated to reduce the average electrical consumption by 3.3 MW during operation; up to 20 GWhr per year.

Although the programme is just starting, thoughts on how to layout and construct such a device are well underway. A possible layout and configuration under consideration is shown in Figure 4.

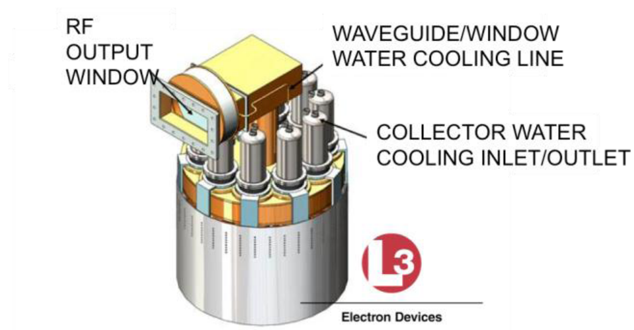

Figure 4: Possible configuration for a 1.2 MW multi-beam IOT under consideration. Courtesy of L-3 Electron Devices.

MODULATOR

The klystrons will be powered with pulsed klystron modulators where both voltage and current are pulsed, but for IOT's the voltage may be kept constant and only the current is modulated.

For the klystron modulators, ESS is following two development and procurement strategies in parallel:

- <u>Strategy I</u>: Procurement of commercial modulators, rated for an average power of 300 kW (330 kVA), able to power two 704 MHz klystrons in parallel;
- <u>Strategy II</u>: Development of a Stacked Multi-Level (SML) topology rated for an average power of 600 kW (600 kVA, unitary power factor), to power up-to four 704 MHz klystrons in parallel.

Table 2: Summary of Required or Expected Main RF Parameters

	Klystron 352 MHz	Tetrode* 352 MHz	Klystron 704 MHz	IOT 704 MHz
Peak Output Power (MW)	2.8	400	1.5	1.2
Frequency (MHz)	352.21	352.21	704.42	704.42
Gun	Diode gun	Filament	Diode gun	Gridded Gun
Pulse length (ms)	4	3.5	4	3.5
Rep. Rate (Hz)	Up to 14	Up to 14	Up to 14	Up to 14
Maximum Beam Voltage (kV)	115	18	115	50
Efficiency at Nominal Power	≥ 55%	> 65%	> 60%	> 65%
- 1dB Bandwidth (MHz)	≥ +/- 1	≥ +/- 3	≥ +/- 1	≥ +/- 1
Gain (dB)	≥ 40	>15	≥ 40	≥ 20

* Combination of two 200 kW tetrodes

The adoption of the SML topology, would reduce the total number of modulators by approximately a factor of two with respect to the 330 kVA modulator.

It is estimated that this reduction in the number of modulators would reduce cost by about 20%. Since the SML topology uses mainly standard of the shelf, low voltage power electronic components widely used in many industrial applications, their cost effectiveness is increased further.

A further advantage of the SML topology is its ability to power both klystrons with pulsed voltage or IOT's with either pulsed or DC voltages.

INTERLOCK SYSTEM

The local protection system (LPS) is designed to prevent damage to the RF equipment within each cell and RF chain and will also prevent any damage to other equipment related to the RF station (klystron, modulator, RF distribution and LLRF) where agreed, typically where a fast shutdown of the RF is required, e.g. Cryomodule arc detection. The LPS (local protection system) works independently from the other accelerator systems but can be controlled and interrogated through the main control system and via local human machine interface.

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