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OVERVIEW AND STATUS OF ESS RF SYSTEMS

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Abstract

The proton linac, for the European Spallation Source (ESS) currently in construction, will be powered by 155 high power RF systems. The RF systems will ultimately deliver in excess of 130 MW peak power, 5 MW of average power to a mixture of normal and superconducting accelerating structures at 352.21 and 704.42 MHz. ESS is a long pulse machine and will operate at 14 Hz with beam pulses of 2.86 ms. This paper will introduce the scope, system design and key technologies of the RF systems being deployed along the linac. We will present the installation and test status as well as initial experience from the operation of the first RF systems used for conditioning and first commissioning runs with beam. The RF systems have been designed to be as energy efficient as practical and we will present the results of a selection of the efficiency measures undertaken at ESS.

INTRODUCTION

The RF requirements for ESS [1−3] vary for the accelerating cavities along the linac. All RF systems have been designed for modularity to keep as many of the sub-systems the same from one section of the linac to the next. In general, each RF system contains a high power amplifier stage, a pre-driver stage, a fast and a slow interlock system, a low level RF system, a DC high power source and the RF distribution system. To maintain flexibility when setting up the linac, each RF system is connected to a single accelerating cavity allowing the voltage in each cavity to be independently regulated. A number of smaller sub-systems are deployed including arc detection, systems to detect multipacting in the accelerating cavities, RF switches for system and people protection, klystron auxiliaries and signal monitoring. At the nominal average beam power of 5 MW 155 pulsed high power RF systems are needed. The proton beam current is 62.5 mA. The accelerating structures are: Radio Frequency Quadrupole (RFQ); Medium Energy Beam Transport (MEBT); Drift Tube Linac (DTL); Spoke Cavity (SPK); Medium/High-Beta Cavity (MB/HB). The RF power sources are summarised in Table 1.

KEY SYSTEM TECHNOLOGIES

RFDS

In total, the ESS RF Distribution Systems (RFDS) contain more than 5000 pieces of waveguide components including high power loads and circulators [4]. To cater for the two different frequencies, 352.21 and 704.42 MHz and varying power requirements, both full and half height WR2300 and full height WR1150 waveguides are used for the klystron based systems and rigid 1-5/8” coax is used for the MEBT amplifiers. Each system includes a waveguide shutter switch to allow for local testing of the amplifier by isolating the amplifier from the accelerating cavity. The majority of the RFDS systems have been installed and tested with the exception of the last 40 RF loads and circulators which were deferred due to budget constraints.

Table 1: High Power Amplifier Technology

	Number	High Power Technology	Peak RF Power
RFQ	1	Klystron	2.9 MW
MEBT	3	Solid State Amplifier	30 kW
DTL	5	Klystron	2.9 MW
SPK	26	Tetrode	400 kW
MB	36	Klystron	1.5 MW
HB	84	Klystron	1.5 MW

Each waveguide run contains more than 25 individual components and each has a return loss of 30 dB or better. An important parameter for the accelerating cavity is the external quality factor and to ensure that it is not significantly affected by the waveguide system, each full waveguide run is tuned to achieve a return loss of 30 dB or better corresponding to a Voltage Standing Wave Ratio (VSWR) of 1.065. Figure 1 shows a typical cell with RFDS runs between the klystrons in the RF Gallery and the cavities in the tunnel.

Despite the theoretical power margin for the waveguide components special care is needed to ensure that all components are clean and free from dust and burrs. All the systems have been tested at full nominal power under full reflection at various phases. At this stage, arcing in several components were observed, particularly in the more complex components such as the shutter switches, high power phase shifters, circulators, but also in standard e-bends which had been manufactured leaving a sharp internal edge causing significant field enhancement.

To protect the systems and determine the location of the arcing, ESS uses three different arc detector technologies; two commercially available and one in-house development for the most challenging locations [5], Fig 2.

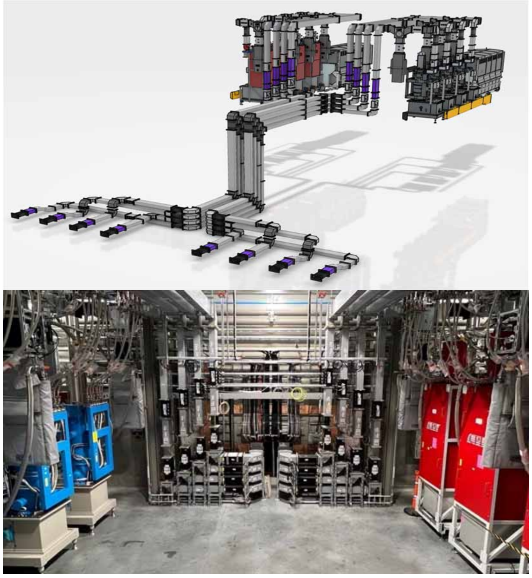

Figure 1: Top: CAD view of a cell of 8 amplifiers. Bottom: View of installation in the RF Gallery.

Additionally, an arc detection system purely for troubleshooting was developed in-house. The system, based on sound propagation, pin points exactly where in the RFDS system the arcing is taking place, before opening up for full inspection.

Figure 2: ESS production of two arc detectors with 1 lux sensitivity, 850 ns reaction time, false trigger filtering, on board full optical path test function, adjustable gain and analogue output monitoring, network connection and HMI.

Solid State Power Amplifier

Three 30 kW pulsed solid state power amplifiers supply the three buncher cavities in the MEBT section. Each SSPA consists of five power amplifier modules. Each module contains eight power stages giving a total of 40 active power devices per system. The individual amplifier modules are hot-swappable and are combined in five 90º hybrid couplers with isolation loads, so each module can operate at full power irrespective of the status of the other modules.

Each SSPA is designed as a turnkey, standalone system and includes a 30kWpeak circulator and load. The output of each amplifier connects to the cavity via a rigid 1 5/8” coaxial line, approximately 30 m long, including reflectometers. Each of the three lines have been tuned and matched.

Klystrons

The RFQ and 5 DTL tanks are supplied from 352 MHz, 2.9 MW klystrons with the main parameters shown in Table 2. Two klystrons are supplied from a single modulator however the RF output power from each klystron is independently controlled.

Table 2: Key Klystron Specifications

	RFQ/DTL	MB/HB
Frequency (MHz)	352.21	704.42
Output Power (MW)	2.9	1.5
Bandwidth (MHz)	≥ ± 1	≥ ± 1
Pulse width (ms)	3.5	3.5
Repetition rate (Hz)	14	14
Efficiency	>53%	>63%
Output VSWR	Up to 1.2	Up to 1.2
Power Gain (dB)	≥ 40	≥ 40
Perveance ($A/V^{-3/2}$)	$1.3*10^{-6}$	$0.6*10^{-6}$
Maximum HV (kV)	110	115

The MB and HB linac sections operate at 704.42 MHz. The power-to-beam required varies along the length of the linac as shown in Figure 3 and in addition, a power margin of up to 30% for RFDS losses and LLRF regulation is assumed. This results in a nominal power at saturation of 1.5 MW for the high energy part of the linac. For the MB and HB RF systems four klystrons are supplied in parallel from a common modulator. All MB klystrons have been installed and installation of the first 20 HB klystrons is underway. A further 20 klystrons are available as spares.

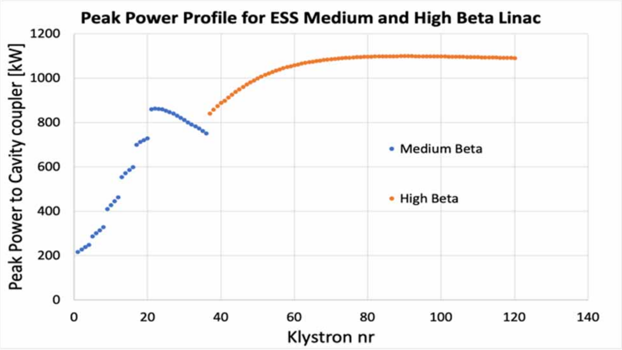

Figure 3: Peak power profile along the ESS medium and high beta linac.

Tetrode Based High Power Amplifier

The double spoke cavity section will be powered by 26 400 kWpeak RF systems at 352.21 MHz [6]. One amplifier consists of two identical branches with solid state drive amplifiers and a tetrode-cavity power amplifier. The power and phase are adjusted at the low power stage to optimise the efficiency when the output signals of two branches are combined in a 3-dB hybrid combiner.

Each amplifier contains the SSAs, an RF distribution module, the Human Machine Interface, screen and control grid power supplies, two tetrodes with their ancillary equipment and the tetrode high voltage supply, including the switching power supply and capacitor bank. It also features a supervisory control system which together with the external local protection system provides protection of the entire RF System and the accelerating cavity. All 26 amplifiers have been delivered to ESS. Prior to installation all amplifiers are tested in a dedicated test stand. Reliability issues were faced during early stage of testing and are being addressed and an extensive program of soak testing is ongoing. Figure 4 shows a spoke RF power amplifier.

Figure 4: Rack layout of RFPS with cabinet panels on rack III and IV removed

Klystron Efficiency

The specified klystron efficiencies at saturation are indicated in Table 2. However, one has to consider that the klystrons may be operated 25% below saturation to provide overhead for the LLRF system. This reduces the operational efficiency to below 40% for the 352 MHz klystrons and below 50% for the 704 MHz klystrons. Additionally, the power profile (Figure 2) means that many klystrons, would operate well below the klystron nominal output power level.

All ESS klystrons have diode guns so reducing the high voltage reduces the DC consumption. However, when operating at voltages lower than nominal, the klystron cavity position is no longer optimal, and the electron beam impedance increases, reducing the efficiency at saturation. To partially recover the loss in efficiency, ESS plans to introduce a mismatch at the klystron output, with each specifically designed for each high voltage level. Together with proper adjustment of the magnetic beam focusing, this almost recovers the efficiency at saturation even when operated at significantly reduced voltages. This was demonstrated on the prototype klystrons from each of the three manufacturers and more recently again for the CETD klystrons installed in the MB linac. Figure 5 shows how the efficiency at saturation and at the point of operation is maintained at lower voltages [7, 8].

In addition to optimising the efficiency of the klystrons, all the RF systems are connected to two separate cooling circuits. One circuit is maintained at 25 ºC for the klystron body, oil tank and solenoids. The klystron collector and high power RF loads however, are connected to the high temperature circuit at 60 ºC which in turn is used for the local district heating system, allowing the waste heat to be recovered and exported.

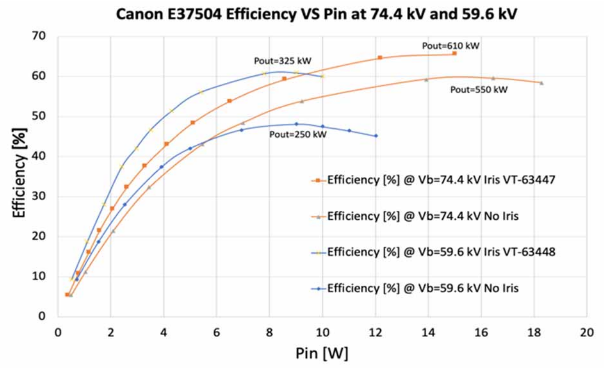

Figure 5: Efficiency at reduced high voltage for a CETD klystron with and without the output mismatch inserted. For comparison, at a nominal voltage of 107.6 kV the efficiency is 65%

RF Local Protection System

Each RF system is protected by a Local Protection System designed to protect the RF components from accidental damage. Two different implementations are implemented, namely a PLC based Slow Interlock Module (SIM), with a response time in the order of ms and an FPGA based Fast Interlock Module (FIM) with a response time < 10 µs, but typically much faster. The SIM is used for temperature and water flow monitoring, for controlling the state machine and for setting up the auxiliary equipment, while the FIM is reserved for arc detection, RF power and multipactor detection and a number of channels have been allocated to protect the accelerating cavities. All signals to the FIM pass through a Signal Conditioning Board for galvanic isolation and to convert all analogue, digital and RF signals to a format compatible with the ADCs on the FPGA.

OPERATIONAL STATUS

The first eight RF systems (RFQ, MEBT 1-3 and DTL 1-4) have been commissioned and are already in use both for cavity conditioning and for the initial operation with beam. The RF systems have performed well with few failures and interruptions. Despite the systems having been specified and optimised for long pulse operation, full performance has been achieved even for very short pulses thanks to the feedforward, feedback and adaptive feedforward systems provided by the LLRF systems [9].

The other RF systems are well underway with the RF systems for DTL5, half of the spoke and MB systems already high power commissioned. The remaining systems up to HB 20 are under test.

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