PRELIMINARY FUNCTIONAL ANALYSIS OF ESS SUPERCONDUCTING RADIO-FREQUENCY LINAC

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Abstract

The European Spallation Source (ESS) is one of Europe's largest planned research infrastructures. This collaborative project is funded by a collaboration of 17 European countries and is under design and construction in Lund, Sweden. Three families of Superconducting Radio-Frequency (SRF) cavities are being prototyped, counting the spoke resonators with a geometric beta of 0.5, medium-beta elliptical cavities (b_g=0.67) and high-beta elliptical cavities (b_g=0.86). The 5 MW, 2.86 ms long pulse proton accelerator has a repetition frequency of 14 Hz (4 % duty cycle), and a beam current of 62.5 mA. The cavities and power couplers are assembled into cryomodules, which are operating using RF sources, cryogenic and water-cooling. This document describes the process of the ESS SRF cryomodule operation, their functions, referred to the operational modes and the different interfaces present in this system.

INTRODUCTION

The choice of SRF technology is a key element in the development of the ESS accelerator. Three types of superconducting cavities are being fabricated; the 56 m long section of spoke cavities operates at 352.21 MHz whereas the 77 m long section medium-beta and 179 m long section high-beta elliptical cavities operate at 704.42 MHz. All the SRF cavities operate in saturated He II bath at 2 K, whilst their power couplers require cooling by helium vapour at the range from 4.5 K to 300 K. The SRF linac accelerates the proton beam from 96 MeV as input energy of the 13 spoke cryomodules, to 216 MeV at the inlet of the 9 medium-beta elliptical cryomodules and to full energy at 2.0 GeV outlet of the 21 high-beta elliptical cryomodules. The ESS linac is fully segmented and cavities are grouped into cryomodules; with two spoke cavities and four elliptical cavities per cryomodule.

Within the framework of the ESS-CEA-IPNO cooperation agreement, technology demonstrators are being designed, fabricated and tested for the spoke and the elliptical cavities and cryomodules. Those demonstrators will validate the technologies to be implemented for the ESS SRF linac series production.

The fabrication, the test, the assembly and the operation of each SRF cavities and cryomodule components shall comply with ESS requirements. The disciplines covered by the requirements are described elsewhere [1].

The operating modes for the cool-down, warm-up, emptying and cold stand-by will be validated during the commissioning phase of the ESS tunnel [2]. The SRF linac operating conditions are derived from the requirements and shall be verified for each operating modes. System, sub-systems, interfaces, process variables, local interlocks, alarms and control state diagrams are being identified. The choice of the control hardware, the electronics and SRF accelerator components must comply with industrialisation abilities. Operating modes need to be defined. Once they are properly defined, it is possible to define in detail the controls architecture to identify the processes. The integration of these local control systems into the Integrated Control System (ICS) will be done using ESS standard controllers and EPICS (Experimental Physics and Industrial Control System) controls framework. The states diagrams for the process control logic are obtained using the operating modes definition. This logic will be implemented in PLCs.

This paper describes the preliminary functional analysis of the process (operating modes and transitions between them) and the interfaces with other systems like cryo-distribution system (CDS), vacuum, RF, utilities and control system.

PROCESS AND SRF CRYOMODULE FUNCTIONAL ANALYSIS

Cryomodule Functionality

The proton acceleration is provided along the beam line by individual control of the spoke and elliptical cavities electro-magnetic field. The cavity helium tank bath temperature and pressure, the power coupler antenna water-cooling can be controlled independently from one cryomodule to the next one. Only the beam vacuum is common to all cryomodules and regulated separately.

The helium provided by the accelerator cryogenic plant (ACCP) is delivered to the cryomodules through the CDS. It consists of the cryogenic distribution line (CDL) running alongside the linac for transfer, which supply/return from/to the valve boxes [3], interfacing with each individual cryomodule. Each valve box is equipped with a set of valves allowing for warming up the linked cryomodule while keeping the rest at cryogenic conditions. The CTL provides the cryomodules with supercritical helium at 4.5 K and 0.3 MPa. During cool-down and filling, the helium is expanded to 0.14 MPa whilst during nominal operation the required 2 K temperature level is created by pre-cooling the 4.5 K helium in a heat exchanger and throttling in a Joule-Thompson (JT) valve, being the vapors pumped back by cold compressors in the ACCP at 31 mbar. The heat exchangers and JT valves are located in the valve boxes for the spoke SRF section and in the cryomodules for the elliptical SRF section [4]. The regulation of the thermal operating conditions of SRF cavities, is performed by a control loop acting upon cryogenic controlled valves and dedicated process variables.

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The Process and Instrumentation Diagram (P&ID) shows the instrumentation and equipment needed to operate each sub-system [2]. A similar P&ID is used for the spoke and elliptical cavity cryomodule operating modes. The P&ID vehicles the information necessary to operate individual cryomodule and is used to define the operating modes, construct the states diagram for the controls logic and the local interlock.

The overall functional analysis makes use of the P&ID to capture the interfaces with other systems, the operating modes and to identify the thresholds used for the different phases of operation. The states of the control system are defined according to the operating modes and the transitions between them. In addition, alarms and interlocks are identified and will be validated during the first test of the technology demonstrators.

The functional analysis supports the Reliability, Availability, Maintainability and Inspectability (RAMI) analysis and the Failure Modes and Effect Analysis (FMEA) of the given systems.

SRF Cavity Functionality

The SRF technology used for the ESS SRF cavities and cryomodules are based on extensive research and development [5]. The SRF cavity package is composed of the cavity itself, the power coupler and the Cold Tuning System (CTS). Each cavity is tuned using one CTS, which gathers fast tuning systems using 2 piezo-actuators to compensate for Lorenz Force Detuning (LFD) and slow tuning system using and stepper motor to tune the cavity before the beam operation. One pick-up probe monitors the accelerating voltage on each cavity.

Each power coupler provides up to 1.1 MW of electro-magnetic energy to the SRF cavity [5]. The power couplers are equipped with vacuum gages, arc detectors and electron detectors. Some of these signals are used as inputs for the interlock of RF system.

The requirements defined for the RF system, the cryogenic system and the vacuum system will be partially validated during the prototyping phase. The beam commissioning of the SRF linac will provide the ultimate validation of the integrated SRF linac.

SRF CRYOMODULES INTERFACES

The functional analysis of the cryomodules is fundamental to achieve a proper integration of the RF, cryogenic, vacuum and control systems. Also, the definition of the interface between the cryomodule and those systems shall comply with distinct requirements. [1]. Therefore, in the following we explicitly describe the physical and functional interfaces between the systems.

Interface with the RF System

The cryomodule RF system is composed of the high-power RF and the low-level RF (LLRF) systems. The high-power RF (klystrons and modulators) is defined elsewhere [6]. In addition, the bias system (and door-knob) inverses the polarity of current, to remove possible multipacting. A power supply is used to activate the bias system. In this context, the physical interface between the RF system and the cryomodule is located at the door-knob installed on each power coupler. The main function of the LLRF and high-power RF is to control the resonance frequency of the SRF cavity.

The failure scenarios of the RF sources are prevented thanks to the RF Local Protection System (LPS). Two arc detectors, installed on each side of the power coupler ceramic window, beam vacuum gages and one electron detector are used to interlock the RF system and the machine beam operation.

Interface with the CDS

Each cryomodule is connected to the CDS via a multi-channel vacuum-insulated branch cryoline, so called jumper connection. Four supplementary lines to the CDL allow for a complete operability of the cryomodules, allowing for example: to collect gases from pressure relief devices in case of overpressure, supply and return gas for purging and purification and to collect gas from the power coupler double wall cooling.

The physical interface between the cryomodule and the CDS is located in the horizontal arm of the jumper connection, which facilitates the testing, transportation and final installation of the cryomodules and CDS's sections.

The function of the interface between the cryomodule and the CDS is to provide the required cooling power at given temperature levels as well as to regulate the cryogenic cooling of the Niobium SRF cavity helium tank and the cooling of the power coupler double-wall. The functional interface requires a number of operating modes (Fig.1), which are grouped as follows:

Operation modes for the whole linac:
• Purging and purification of all the cryogenic circuits • Cool down of the whole linac from 300 K to 4.5 K • Cool down of the whole linac from 4.5 K to 2.0 K • Warm up of the whole linac from 2.0 K to 4.5 K • Warm up of the whole linac from 4.5 K to 300 K • Stand-by at 4.5 K • Stand-by at 2 K • Nominal operating mode
Singular modes
• CDS insulation vacuum pumping • CM insulation vacuum pumping • Beam vacuum pumping • Purging and purification of the linac cryogenic circuits
Modes for a single cryomodule
• Warm up of a single CM from 4.5 K to 300 K • Purging and purification of a CM's cryogenic circuits • Cool down of a single CM from 300 K to 4.5 K
Abnormal modes:
• Cavity quench • Beam line vacuum failure • CM insulation vacuum failure • CDS insulation vacuum failure

Figure 1: List of operating modes of the linac.

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All the failure scenarios are prevented by alarms and local interlock system, which are complementary to the control logic in the PLCs. Safety pressure relief valves are protecting the SRF cavities from possible over pressure of the superfluid helium bath.

Interface with Vacuum System

The physical interface between the cryomodule and the beam vacuum relate to the operation of the vacuum isolating gate valves, which are installed at the extremities of the cryomodules. In addition to this, the Niobium wall of the cavities can also be considered as an interface. The control of the superfluid helium pressure provides element to estimate the possible wall desorption, while the beam vacuum pumping capacity is determined using the wetted area.

The overall beam vacuum condition is monitored by vacuum gages installed at the power couplers and in the warm section located between the cryomodules.

The failure scenarios are mitigated and minimized with the use of fast acting valves located at the inlet and outlet of the SRF linac sections. During maintenance modes, the vacuum isolating gate valves are closed in order to protect cavities from possible pressure increase.

In addition to the beam vacuum, the insulating vacuum of the cryostat is maintained by the use of turbo-molecular pumps attached to the vacuum vessel of each cryomodule and backed up by primary pumps collecting from the primary vacuum manifold which groups various cryomodules. In case of helium leak to the insulating vacuum, the pumping capacity is increased.

Interface with Utilities

The interfaces between the cryomodule and the power coupler antenna water cooling system can be controlled independently using a series of temperature, pressure and mass-flow measurements.

SIGNAL INTEGRATION IN THE CONTROL SYSTEM

The functional analysis of the process defines the states diagram for the control logic of the process. Process variables are identified and operating limits are listed. However, for the complete operation of the SRF Linac other interfaces need to be considered. These interfaces, described below, allow for a general controls architecture for the SRF Linac to be derived [2].

Cryogenic Process Control

The inputs for the state diagram implementing the thermal operation of the cryomodules come for a set of instrumentation in the cryomodule and the CDS. The signals from the instrumentation need to be conditioned prior to be sent to the control system. The conditioning is made of two steps:

a) Conditioning: implies signal transducing, acquisition through and ADC and possibly in some cases FPGA processing.

b) Communication: consists of converting the signals to a format readable by the controller and, together with the acquisition of the controller, forms the interface to ICS. The chosen controllers are PLCs where the state diagram and the regulation needed is implemented. This PLC will be integrated into EPICS such that the used variables will be monitored. Some of the will be also used as alarms.

After a FMEA considering failure scenarios regarding the insulation vacuum and the water-cooling systems, the local interlock system will be designed. This system will be PLC based. So the interface is equivalent the PLC-based systems mentioned before. Moreover, this protection system may have also interfaces with the other two protection systems related to the SRF Linac: Machine Protection System (MPS) and RF LPS. Both are critical to secure the operation of the linac. Vacuum System control.

The beam line vacuum is treated separately within the overall vacuum control system. It uses the analogue signals from vacuum controllers as inputs of the vacuum interlock system, which is PLC-based. The operation and monitoring (also alarms) of the system will be based on serial ports integrated into EPICS controllers. Therefore, the interface is the connection between the vacuum controller and the EPICS controller. However, the insulation vacuum will be included in the PLC in charge of the process control mentioned before, as it is closely related to it. The interface in this case is between the PLC I/O and the vacuum instrumentation.

Water-cooling System Control

It is also handled in the process PLC, so the interface is similar to the vacuum insulation case.

Tuning System Control

A Delta Tau Geobrick LV IMS-II drives the stepper motors for the technical demonstrators. These units are integrated into the EPICS control system and serves as the interface to ICS. A process for standardization of motion control solutions is on-going at ESS. The fast piezo-tuners will be driven from a board compatible with the MicroTCA4.0 standard, same as the LLRF system. That means that the chosen controller will be MicroTCA-based. The board driving the motors sitting in the controller is in this case the interface to ICS.

RF System Control

This system has its own local controls per each RF cell. It is made of the LLRF system and the local protection system (LPS). This system is integrated into an EPICS controller forming an interface with the ICS.

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