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A STATE MACHINE SOLUTION TO CONTROL SUPERCONDUCTING CAVITIES

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Abstract

For the commissioning of the SPIRAL2 accelerating cavities at GANIL, a whole EPICS control-command system has been developed to start the radio-frequency (RF) system. The description of the RF constraints, the functions performed will be discussed to understand the operation of state machines that have been developed. The first results of the commissioning of the control-command of the cavities will be presented.

INTRODUCTION

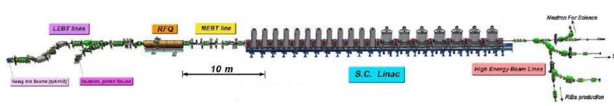

Figure 1: SPIRAL2 facility.

Phase 1 of the SPIRAL2 project includes two ion sources, a Radio frequency quadrupole (RFQ), a linear supra conducting accelerator (LINAC) and two experiment rooms Fig. 1. SPIRAL2's LINAC is capable of accelerating particles such as protons, deuterons, or ions from helium to nickel. The control command system is made up of 40 RF systems and is controlled by 70 tuning applications and 70 programmable logic controllers (PLC) [1]. Very early in the project phase of SPIRAL2, the choice was made to control RF systems using state machines with the State Notation Language (SNL), a domain specific language provided in the EPICS framework. The following article will present the global control command architecture for RF systems. It details the significant contribution of state machines, and the advantages of EPICS. The solutions put in place to control superconducting cavities and the radio frequency quadrupole will be detailed. In July 2019, the French Nuclear Safety Authority authorized to start the LINAC and beam commissioning. First results of the RFQ and LINAC RF commissioning are briefly described.

THE DIFFERENT TYPES OF CAVITY

- Radio frequency quadrupole : this continuous wave warm cavity is a 4 vane RFQ type, 5m long, that can accelerate a 5mA beam of proton or deuteron and a 1 mA beam of light ions (Q/A>1/3) up to 0.73 MeV/A.
- Rebunchers : 3 rebunchers providing up to 120 kV of effective voltage are located in the Medium Energy Beam Transport to keep the beam longitudinal phase dimension
- Supra conductor cavities: the SPIRAL2 LINAC is composed of two families of SC Quarter Wave resonators, providing an accelerating field of 6.5 MV/m and coupled to transfer 7 and 12 kW to the 5mA beams [2].

THE SPIRAL2 RF CONTROL COMMAND SYSTEM

The EPICS framework was chosen from the pre-project phase in order to standardize the software developments of the SPIRAL2 community. A considerable effort has been made to organize and modelize equipment interfaces in order to facilitate high-level applications development [3, 4]. The ease of use of the Channel Access (CA) communication protocol which allows very simple access by name to facility beam process values, names Process Variable in EPICS (PV), has considerably reduced the development effort for control applications. These choices allowed an integration of the different projects in progress, such as SPIRAL2, NFS, S3 [5]. The RF control-command system is divided into 6 subsystems: cavities, low level RF (LLRF), frequency tuning systems (FTS), amplifiers, waveguides, and global amplification channels. The LLRF plays a central role in cavity regulation and can be accessed by high level control-command beam tuning applications Fig. 2 [6].

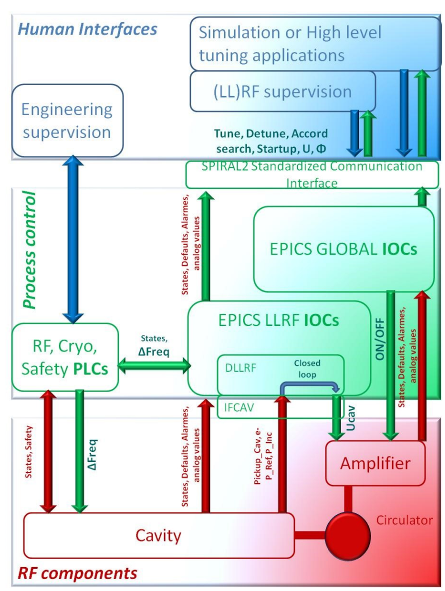

Figure 2: Spiral2 RF control command architecture.

FINITE STATE MACHINES (FSM)

State machine programming methods appeared in the 1990s. Finite state machine method is based on the prin-

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ciple of having a finite and sequential number of transition states. FSMs are particularly adapted to the complexity of the actions and sequences to be performed on RF subsystems. In addition, the EPICS framework has the tool to develop a state machine: the sequencer support module [7]. For these reasons, algorithms to condition a power coupler or cavity, perform a frequency tuning search or a field rise are developed with this principle.

SPIRAL2 RF STATE MACHINES

State Machine Overview

The state machines list below are a typical implementation of the requirements. Most of them is implemented in LLRF EPICS IOCs, as close as possible to the cavity field regulation process. Each type of cavity could proceed with a

- Power coupler conditioning
- Frequency tuning research
- Cavity conditioning and field increase
- Cavity automatic actions

state machine procedure. Following several years of vacuum storage of the supra cavities, the **power coupler conditioning** procedure is a function that was required to ensure the proper conservation of the power coupler before the cavities commissioning. The **frequency tuning research** procedure is needed to set the cavities at the nominal 88,05MHz frequency. For **cavity conditioning and field increase** procedure, the field rise was coupled to the conditioning function. The idea is to intelligently monitor cavity sparks. Indeed, from one start-up to the next, conditions may differ if maintenance operations have disrupted the quality of the internal surfaces of the cavities. **Cavity automatic actions** is the high level process given to operators to easily control cavities before applying tuning parameters from high level tuning applications.
Table 1 shows the procedures compatibility with the SPIRAL2 cavity type. Meaning of symbols is **V**: Validated,

Table 1: State Machines and Cavity Types

State machines	**RFQ**	**Rebunchers**	**Supra cavities**
Power coupler conditioning	na	na	V
Cavity conditioning and field increase	V	na	TBD
Frequency tuning research	na	V	TBC
Automatic actions	TBD	TBV	TBV

na:not affected, **TBD**:To Be Defined, **TBC**:To Be Confirmed, and **TBV**:To Be Validated.

Power Coupler Conditioning

As illustrated in Fig. 3, the coupler conditioning procedure consists in starting the high frequency with a very low power before increasing useful cycles, with a progressive increase in power over each cycle until a maximum power is obtained in continuous mode (100% cycle).

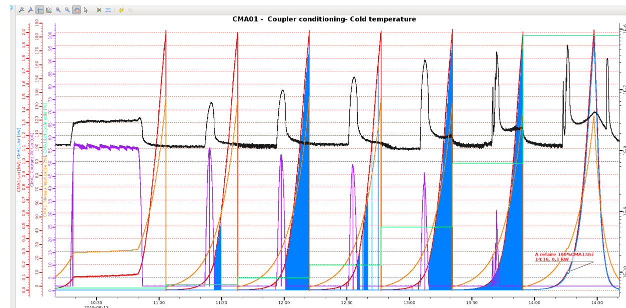

Figure 3: Coupler conditioning graph.

The procedure switches to the next cycle when the maximum power is reached. It is carried out with a return to minimum power without any other precaution. When the maximum amplitude of the last useful cycle (100%) is reached, a progressive decrease in power is performed. The thresholds parameters and useful cycles to be processed can be set at any time. The degradation of the vacuum or a current induced on the coupler beyond the set thresholds induce both a power rise freeze, waiting for a nominal situation. If these degradation exceed the material tolerance limits, the LLRF safety device stops the procedure.

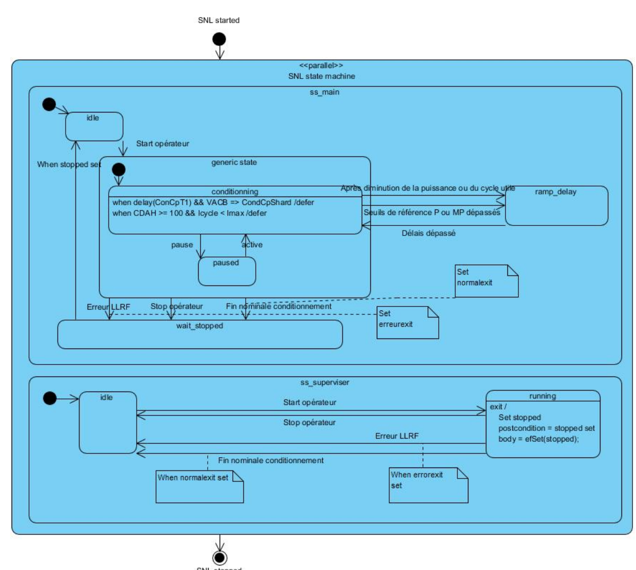

Figure 4: UML state diagram for coupler conditionning.

Two state machines can interact with each other with only two EPICS event flags as shown in Fig. 4. The first state machine manages the conditioning states while the second one manages the user actions states. We can see that the central role of the conditioning state is isolated from the other

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states, that extremely simplifies the software SNL code that must be written. Each event, which can be simply monitored throw an EPICS process variable, makes a transition to an other state.

Frequency Tuning Research

After checking required conditions of cavity subsystems, the procedure turns the TFS in tuning search mode. This one will therefore scan the position of the motor, which will be monitored by the procedure. RF is set ON as soon as the TFS starts scanning. Exceeding the cavity field by the value predefined at initialization, indicates that the cavity is close to its resonance frequency. The TFS then went into tuning maintenance mode. This mode allows the cavity to be held exactly and automatically at its resonance frequency. The TFS thus completes the last movements of the motor to find exactly the resonance frequency.

Cavity Conditioning and Field Increase

For the RFQ cavity, this procedure uses a variable frequency system (PLL loop) to raise the field strength to the nominal value. It manages the initial rise as well as the resumption of sparks not recovered by the LLRF. When the number of sparks is low enough for the system to achieve thermal stability, the procedure also brings the cavity to its nominal frequency and switches the operating mode to the nominal TFS. For SC cavities, this procedure depends on their behavior during the commissioning phase.

Cavity Automatic Actions

After the commissioning phase on site, when the behaviour of the different types of cavities is completely controlled, a higher level state machine will be set up to orchestrate all actions. This will free SPIRAL2 facility drivers of high RF skills to start the cavities in nominal mode. First tests with a rebuncher cavity demonstrate the feasibility and relevance of the use of state machine concept. The set of these automatic actions will be definitively validated when the machine goes into nominal operation.

CONCLUSION

Procedures which implement a complex behavior between several RF sub-systems can be simply implemented with state machines as described for the power coupler conditioning or frequency tuning research procedures. To keep the benefit of state machine concept, a whole list of states and transitions must be correctly identified during analyze phase.

This concept also implemented inside EPICS with the sequencer module support allows you to write quickly and easily reliable pieces of software. During the phase of software unit tests, failures or improvements were particularly easy to find. The power coupler conditioning procedure worked from the first commissioning sessions with SC cavities. This reliability made it possible to condition 26 power couplers in a record time of 10 days.

Evolution are already under investigation to improve RFQ cavity startup time. The separation of the software code by the programming logic into a state machine has saved a considerable amount of time in the development of the code. This cutting allowed the developers to be very reactive for the modifications requested during the functional testing phases on cavities, especially during the RFQ commissioning [8].

As shown in Table 1, all procedure types have been validated on at least one cavity type, except for the automatic action which is reserved for the operating phase. The relevance of this one remains to be confirmed for the RFQ. Similarly, the first tests on the supra cavities will determine whether the frequency tuning research will remain useful for the operation.

RFQ and rebunchers are currently validated and used for the MEBT beams. The superconducting cavities are currently in the commissioning phase. The first beams in LINAC are expected by the end of 2019.

We expect we will take more and more benefit from this strategy and the first LINAC and NFS beams will be due to the work done on the state machine procedures.

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