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AN OPTIMAL PROCEDURE FOR COUPLER CONDITIONING FOR ESS SUPERCONDUCTING LINAC

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Abstract

An optimal procedure for coupler and cavity conditioning is proposed for the ESS superconducting cavities, which is applicable for different test stands and following installation in the ESS tunnel. A preliminary procedure has been developed and successfully tested at FREIA facility, Uppsala. The preliminary procedure will now be improved by integrating it into LLRF and EPICS control. This will be a joint effort between FREIA and ESS and will be used at the test stands in Lund and on the couplers installed in the tunnel. Developing the conditioning procedures on a common platform offers ESS significant advantages by allowing the procedures to be reused at different sites and by recording data in a consistent format. The details of the procedure, its development and testing will be reported and the future activities will be described.

INTRODUCTION

The European Spallation Source (ESS) will use a total of 26 double-spoke cavities in the medium energy region, at 352.21 MHz, 36 medium beta elliptical cavities at 704.42 MHz and 84 high beta elliptical cavities also at 704.42 MHz [1]. ESS spoke cavity is designed and fabricated by IPNO, while series spoke cryomodule testing will be carried out in the Facility for Research Instrumentation and Accelerator development (FREIA), Sweden[2]. Production of series elliptical cavities is undertaken by INFN-LASA and STFC and series cryomodule assembling will be done by CEA, while final elliptical cryomodule testing will be performed in Test Stand 2 (TS2) at ESS site in Lund, Sweden.

As variety of RF tests carried out in different test stands all over European and very limited time is foreseen for commissioning cavities in ESS tunnel, it is crucial to develop optimal cavity commissioning/test procedures based on common hardware and software platform, aiming to reuse the procedures in different test stand and ESS tunnel. Based on common platforms, it will be also easier to share the knowledge and data between different test stands and ESS tunnel.

While typical coupler conditioning procedures in test stand focus mainly on reaching the required power level at required mode, the "optimal" procedures emphasize procedures reusing, knowledge accumulation and consistent result interpretation over different stages of cavity and cryomodule life cycle (test, commissioning, operation and maintenance).

During power coupler/cavity conditioning stage, a wide variety of RF modes (in term of RF pulse length, RF pulse peak power, and repetition rates) will be employed. Detailed and valuable information will be obtained and would benefit much for characterizing RF/Cavity dynamics. This will be critical when it comes to fault tolerance strategies and high efficiency operation strategies. It is thus equally important, if not more, during the stage of optimal procedure development, to identify and find 'smart' solutions to obtained adequate information to understand better cavity system and to get to know its limitations, thereby testing, controlling and operating the cavity system efficiently and effectively.

This paper thus discusses and proposes an optimal procedure for power coupler/cavity conditioning, in the purpose of reusing the procedure in different test stands and ESS tunnel, reducing the time and effort of overall power coupler/cavity conditioning, and finding a smart way to commissioning and operating RF/cavity system efficiently.

WORKFLOW CHALLENGE TO DEVELOP OPTIMAL PROCEDURES

Workflow Challenge with Multi-Stakeholders Collaboration

In theory, it is probably true that maximum benefit would achieve if the same procedure based on the same hardware and software platform can be applied in all test stands and ESS tunnel, however, it is always not operational in practice. We have to focus on what is concretely possible in short term to achieve in test stands with existing infrastructure, preferable software/hardware platform by technical experts, and available resources. It is then easier to work together to address concrete problem faced in development process, by exploring new ideas from all participants and by making best use of technologies already in place. In such context, a more practical workflow for procedure development shown in Fig. 1 is considered at ESS. This workflow is not only valid for coupler/cavity conditioning, but also can be applied for other cavity/RF test and commissioning procedures.

The challenge of this workflow with multiple stakeholders collaboration lies in the fact that, due to different stakeholders are undertaking different tasks and are in different development stages, it is inevitable that different version of procedures based on different platforms will exist. As a result, it becomes challenging and complex to reuse the procedure, to share data and result, and to accumulate knowledge in different test stands and ESS tunnel.

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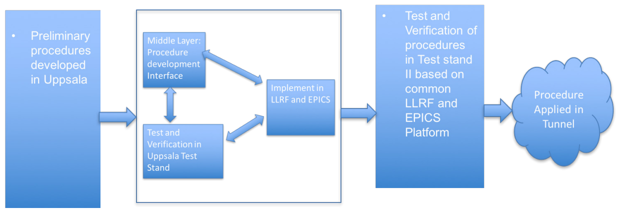

Figure 1: Work flow of procedure development.

Development Interface to Address Challenge

To reuse the procedure based on different software/hardware platforms and to reduce dependency on implementation platforms, a "development interface" is considered. "Development interface" differs from terms already used at ESS such as "requirement interface" and "physical interface" that describe more about responsibility and boundary between two different systems. "Development interface" represents the abstract high-level logical schema of operation procedures, which can be described by a set of events, scenarios and functions, and their interactions between each other in response to external inputs or internal data/command exchange. It helps build common understanding among different stockholders, and acts as basis for programming final procedures in LLRF and EPICS. As the abstract high-level logical schema is independent on implementation platform, it facilitates procedure re-using and sharing. Furthermore, it reduces development time and effort.

For overall cavity test/commissioning procedures, "development interface" can be done in top-down approach, as the high-level design of procedures, or it can be done in bottom-up approach, by abstracting from running procedures in existing platforms. The key point is to ensure there is only one unique "development interface" for one procedure and is understood by all stockholders. In such way, all stakeholders share common framework for procedure development, which reduces dependency on implementation platforms and makes procedure more reusable.

For specific procedure for coupler/cavity conditioning discussed in this paper, bottom-up approach is used. "Development interface" for cavity/coupler conditioning will be abstracted from preliminary procedure running in Uppsala test stand. It will be further modified as high-level programming logic of procedures. Further validation will be done in Test Stand 2 an expect to finally use in all superconducting cavities in ESS tunnel.

PRELIMINARY PROCEDURE DEVELOPED IN UPPSALA

RF-Vacuum Feedback Conditioning System

Primarily, an interlock system is vital to the protection of instrumentations during high power RF conditioning. Some expensive and sensitive RF components, like ceramic window or circulator, are vulnerable to arcing events. Switching off RF power only after arc events cannot eliminate risk of damaging fragile components from destructive pressure burst. In addition, resetting of the system after interlock triggered takes a longer time and consumes lots of human resource.

An automatic conditioning system is thus investigated and the concept is shown Fig. 2. Acquisition system, control system and feedback system help adjust and control testing parameters with respect to the conditions. The condition indicated in the figure is defined by experts, which should at least include both interlock trig threshold and auto conditioning threshold. These thresholds vary from lab to lab as well as couplers to couplers. The acquisition system usually consists of the forward, reflected and transmitted power, vacuum levels and all the interlocked signals. The control system includes software controlling the duty and peak power of pulse, switching on and off the RF power, and resetting system.

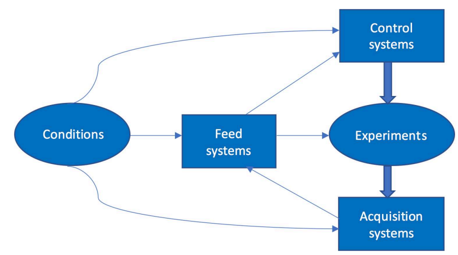

Figure 2: Concept of automatic conditioning system.

In order to reduce damage from destructive factors, the cavity vacuum is chosen as a leading preventive indicator. The automatic conditioning in this case is categorized into RF-vacuum feedback conditioning. The main idea of such RF-vacuum feedback is to regulate RF power as a function of vacuum pressure around the coupler. In this way, vacuum limits avoid local overheating or electrical arcing within the vacuum side, which otherwise would damage the fragile ceramic window in the coupler. A schematic of RF-vacuum feedback conditioning system is shown in Fig. 3. In order to achieve an effective RF-vacuum feedback, following principles need to keep in mind:

- Regulate RF power as a function of vacuum pressure around the coupler as fast as possible.
- Apply a longer repetition period than the vacuum reading delay.

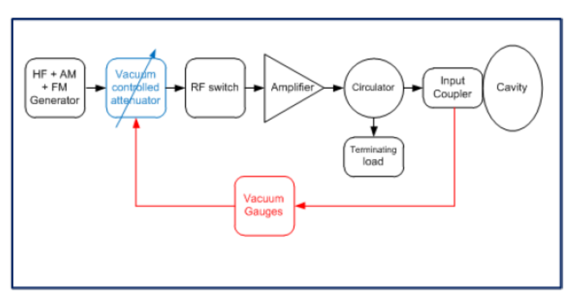

Figure 3: RF-Vacuum Feedback Conditioning Loop [5].

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Implementation and Results at FREIA

Prior to high power test, the power coupler of ESS spoke prototype went through RF power processing both at room temperature and 2K. As mentioned in previous section, in order to reach high efficiency and high availability while reducing time and effort of overall conditioning process, automatic RF-vacuum feedback conditioning system is considered and developed at FREIA. It consists of acquisition system, configuration system, and feedback system. Input power level to RF station can be controlled either manually or by automatic conditioning system, while all essential interlocks are implemented in hardware. The program is based on LabVIEW, with functions reading or writing data from/to EPICS system. The whole conditioning system consists of several modules, to make debugging easier and future upgrading more flexible. The graphic user interface can be seen in Fig. 4 [3].

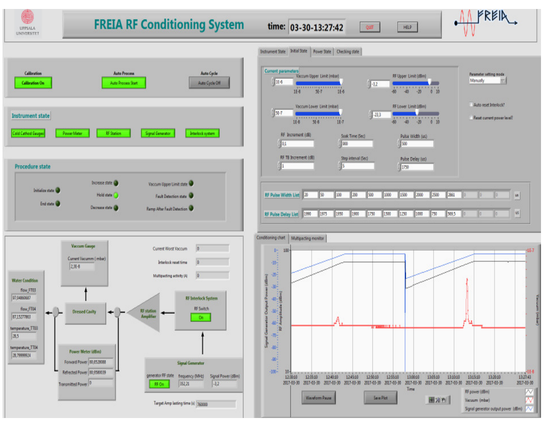

Figure 4: The FREIA RF conditioning control system.

RF power conditioning at FREIA is done in standing wave regime at 14Hz repetition rate with different pulse lengths from 20 to 2860 micro-seconds. During each pulse length, the power is started from a low value and then ramped up step by step depending on various operating parameters. Finally, the maximum power of 120 kW is reached. Two software vacuum thresholds are adopted in this conditioning procedure. As long as the coupler vacuum keeps below the first software threshold of 5e-7 mbar, RF power increases. Once above the first software threshold, the controller holds the RF output until the vacuum is recovered. Otherwise, RF power is decreased by 1dB if the vacuum gets worse, down to threshold 1e-6 mbar. Once the current phase reaches the targeted power, the system keeps the maximum forward power for a soaking time before the input signal is cut off. The next phase should not be executed until vacuum recovers below the first threshold. In parallel, an interlock system protects the RF components independently. Essential detective activities employed in the interlocks are arc, electronic events, temperature and vacuum. The flow chart of FREIA conditioning is shown in Fig. 5 [3].

The warm and first cold RF processing was firstly done at FREIA using IPNO Orsay's system, followed by the new FREIA RF-vacuum feedback conditioning system to verify its performance. All processes used a traditional signal generator driven loop. The warm RF processing procedure before cooldown took about 40 hours, lots of outgassing occurred through the forward power region of 50-80kW at short pulses. At the first phase, the coupler conditioning was finished when 120 kW forward power was reached with 2.86 ms pulse duration. The RF-vacuum conditioning system was then tested with ESS cavity package to verify the logic and related hardware. The overall RF-vacuum system worked as expected: with little vacuum activity, the forward power quickly ramped up to 120 kW with 2.86ms. Good performance of RF-vacuum feedback conditioning system at FREIA indicates that this system is ready for future conditioning purpose.

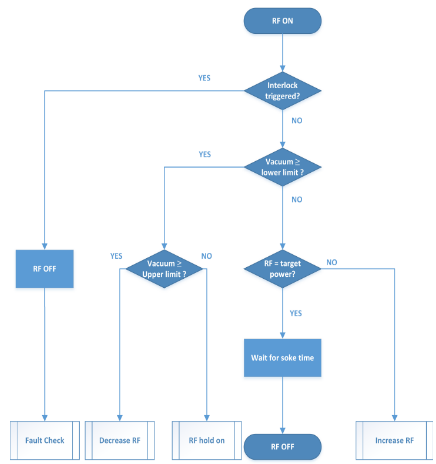

Figure 5: The flow chart of FREIA conditioning.

PROCEDURE UPDATE FOR ELLIPTICAL CAVITIES

As described above, the preliminary procedure developed at FREIA has been verified on ESS Spoke cavity packages and overall the RF-vacuum feedback conditioning worked as expected. The next step is to abstract the high level logical schema from verified operation procedures. For most of elliptical cavities, much higher peak power (up to 1.1MW) is required to deliver to beam than that for spoke cavities. Taking into account of 30% power overhead need for LLRF regulation, and full reflection at the beginning of cavity filling, significant high peak power handling is expected in elliptical cavity/coupler conditioning. It gives rise to tough challenge when applying procedures developed for lower power spoke cavities in higher power elliptical cavities.

Enough care and patience has thus to be taken when drawing the high level logical schema for elliptical cavities. Early implementation similar to that for spoke cavities might be tried in first batch of medium beta cavities as their power level are comparable with spoke cavities, while later implementation could be smoothly evolved in

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the rest of medium beta and high beta cavities whose power levels increase gradually as shown in Fig. 6.

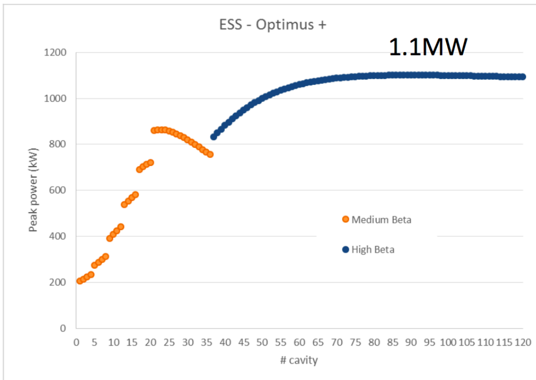

Figure 6: Required peak beam power in ESS elliptical cavities.

It is essential to get enough information from verified spoke cavity/coupler conditioning procedures, in order to abstract high level logical schema. It is equally true to obtain enough input from real elliptical cavity/coupler conditioning, even in their early development/prototype stage. Timely and valuable conditioning information for elliptical cavity can now be obtained in standalone coupler conditioning system at CEA-Saclay, with two back-to-back couplers connected via custom designed box, as seen in Fig. 7.

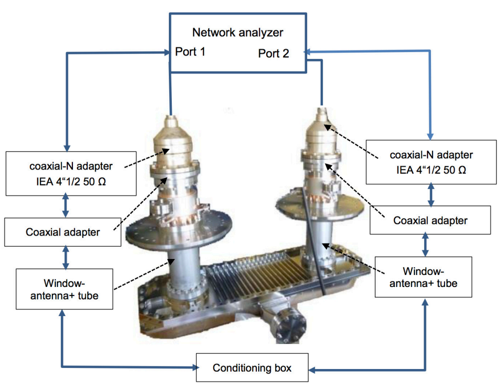

Figure 7: Back-to-back power coupler conditioning system at CEA-Saclay.

The goal of this conditioning system is to be able to provide 2.86ms flat top pulses with a peak power up to 1.1 MW. The applied conditioning sequence is:

- in travelling wave mode (TW) to reproduce the field condition in the operating linac with beam: RF power ramp from 15kW to 1200kW (pulse width from 50 micro-seconds to 3.6 mini-seconds) with repetition frequency from 1Hz up to 14Hz.
- in standing wave mode (SW) to reproduce the field condition in the operating linac without the beam: 2 positions of short circuit (at CEA test stand), RF power ramp from 15kW to 1200kW (pulse width from 50 micro-seconds to 500 micro-seconds, 1Hz), from 15kW to 300kW (pulse width up to 500 micro-seconds to 3.6 micro-seconds, 14Hz).

During the conditioning, several conditions and parameters must be checked and kept under control:

- vacuum levels
- arc detection events on vacuum and air side (the most of these events are expected to happen on the air side)
- Multipacting events
- RF (forward power to the couplers) in order not to exceed the maximum foreseen levels
- Temperature (box, window, water)
- Water flowmeter
- Security signals (vacuum, water)

These practical coupler conditioning experience offers valuable and particular high-power input to abstract high level logical schema, which cannot be obtained directly in spoke cavity conditioning experience. Not only for abstracting high level logical schema, high power conditioning experience will provide will also insight about parameter configuration and system limitation estimation when running conditioning procedure in high power elliptical cavities.

PROCEDURE TEST AND VERIFICATION IN TEST STAND 2

Having verified preliminary procedure in spoke cavities and high-power conditioning information from real elliptical couplers, the high level logical schema of optimal conditioning procedure will be developed. It will be then translated to programming logic to be implemented in LLRF and EPICS platform, and be tested and verified in elliptical cavities in Test Stand 2 (TS2) at ESS site in Lund.

TS2 is responsible for the site acceptance test (SAT) of cryomodules for both medium beta and high beta elliptical cavities. It consists of a radio-protection bunker, a test stand cryoplant and RF power sources, composed by two klystrons and one modulator [4]. TS2 will perform the reconditioning of the power couplers at warm and cold temperatures, as a requirement to ensure the good performance of the cavities in the linac. The radio-protection bunker is composed by 1200 tons of heavy concrete, arranged to form 1 m thick walls all around the cryomodule and equipped with x-rays monitors, to allow the reconditioning of the couplers at safety conditions.

Design problems and construction defaults of the couplers can be the cause of many physical phenomena when the coupler is placed under vacuum and crossed by the HF. These phenomena can be damaging for delicate parts of couplers such as ceramic windows providing barrier between the vacuum cavity and the atmospheric pressure. The function of the couplers can be guaranteed only after a RF conditioning, consisting in the gradual adaptation of

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the coupler to withstand electromagnetic fields created by the passage of the RF power, it reduces the violence of these phenomena and allows to identify some couplers with construction problems. The conditioning allows the gradual reduction of these phenomena by a controlled increase of the power, it must be SAFE and SWIFT [5].

ESS is committed to work in the next stage of the Experimental Physics and Industrial Control System (EPICS) software, as a contribution to the accelerator community, and so the cavity conditioning program is also being integrated into EPICS, using IOC for the control algorithms and CSS-BOY for the operator interface. ESS will profit the development of the MTCA.4 technology to implement the LLRF system that will be used, among other things, to read the signals for the coupler conditioning.

Even though the final implementation of coupler/cavity conditioning optimal procedures will base on LLRF and EPICS platform, the top-level sequence/algorithm realization might rely on the third-party software like C, Python or JavaScript due to that some computation might need in this optimal procedure.

POWER COUPLER AND CAVITY CONDITIONING AS A STAGE FOR ONLINE RF DYNAMICS IDENTIFICATION

By choose appropriate RF input waveform in cavity filling time, online power amplifier (such as klystron, IOT) input-output characteristics could be obtained with direct measurement on power amplifier input power and output power.

In this method, instead of using a pure pulse shape as driver signal for coupler conditioning, appropriate RF input waveform with exponential slop or linear slop in cavity filling time is chosen to feed the power amplifier, in order to generate all power levels from zero to full power. By measuring RF powers before and after driver amplifier, power amplifier, and circulator (signals are sampled in LLRF system), online characteristics of system dynamic such as nonlinearities, return loss and bandwidth variations will obtain. It gives valuable information to operate system at nonlinearities and to frequently change the operating points. The shape of the waveform has to be chosen carefully so as to be long enough to get adequate data sampling but short enough to increase efficiency.

RF dynamics in different RF modes will obtain in this method, as numerous RF modes (with different RF pulse length, different RF power level, and different RF repetition rate) usually have to apply in power coupler conditioning in order to achieve required power level.

CONCLUSION

An optimal procedure for SC coupler and cavity conditioning at ESS is discussed and details are given. A "development interface" is propose to reduce dependency of implementation platform, facilitate procedure reuse, and save development cost and time. Further procedure development will base on verified preliminary procedure in spoke cavity and valuable high-power experience from real elliptical couplers. Final implementation will be based in LLRF and EPICS platform. It is also discussed to make online RF dynamic identification by taking advantage of enriched RF modes in power coupler and cavity conditioning.

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