INVESTIGATION TO IMPROVE EFFICIENCY AND AVAILABILITY IN CONTROL AND OPERATION OF SUPERCONDUCTING CAVITY AT ESS

Rihua Zeng, European Spallation Source ERIC
Olof Troeng, Lund University, Sweden

Abstract

The higher efficiency and higher availability (fault-tolerant oriented) of RF & Cavity system (with beam loading) to operate at, the more dynamic details needs to be identified, so as to have the abilities (a) to work at nonlinearities, (b) to work close to limitation, and (c) to change operation point quickly and correctly. Dynamic detail identifications rely heavily on high precision measuring and characterizing basic cavity parameters (Q_L, R/Q, dynamic detuning, phase and amplitude) and system behaviours under beam-RF-cavity interactions. It is especially challenging to characterize these dynamics under varying operating points or environment. Advanced technologies in LLRF and ICS providing real time/online characterizing will be the key enablers for addressing such challenges. However, to be successful, the deployment of these technologies must be embedded within local conditions taking into account available resources, existing hardware/software structures and operation modes. Several improvement approaches will be introduced. For example, 15% or more energy efficiency improvement at ESS will be obtained by reduction of power overhead and optimization of operation.

INTRODUCTION

The European Spallation Source is a planned neutron source to be built in Lund, Sweden, with a start of neutron production in 2019. The performance goals are an average beam power at the target of 5 MW, with a 62.5 mA current and a pulse repetition rate and length of 14 Hz and 2.86 ms, respectively. It is to be built as a green plant, which places stringent demands on powers conservation and recycling of energy. This will be achieved by careful design and modern power recapture methods, such as using the cooling water to heat the surrounding municipalities. This also places stringent demands on the low level RF systems, especially as the plant at the same time has an operational goal of 95% availability and a comparably short time from start of final design to commissioning. Here we will describe some of the consequences these demands have on the RF, Cavity and LLRF system, and the proposed solutions and development projects that have started in order to reach this goal.

ENERGY EFFICIENCY

Typically linear accelerators use klystrons as RF power amplifiers, as these can deliver the power to get necessary accelerating gradients in the cavities of the Linac. In feedback control mode, to facilitate the control of the phase and the amplitude of the fields in the cavities, the klystrons are typically run far below saturation in a linear region of operation to leave some power overhead for regulation. Such overhead is not necessary if klystrons are operated in open loop. There are quite some electron machines (MAXIV, PSI, CLIC, etc.) in which klystrons are operated at their saturation point.

To better describe system efficiency, the power overhead in this paper is defined in a wide range: the difference between the maximum RF amplifier output and the power delivered to the beam, including necessary margin for error compensation and transient behaviour in feedback control, and also the power dissipation in RF distribution system. The operation points of klystron in traditional accelerators are often chosen at lower than 70% of saturation (where klystrons input-output power curve are much linear), to ensure adequate power overhead without considering high-order dynamic details. In JPARC, great effort has been put to figure out dynamic details of klystron and normal conducting cavities under heavy beam loading. As a reward for their effort, more of their klystrons are able to work at 85% of saturation level, reducing significantly power consumption. Advanced technologies in modern high performance hardware make these solutions possible, with great flexibility in configuration and short time in implementation.

Within the ESS project we will look into system dynamic details and try every effort to step further, so as to operate the power amplifiers at 90% of their saturation level, as shown in Figure 1.

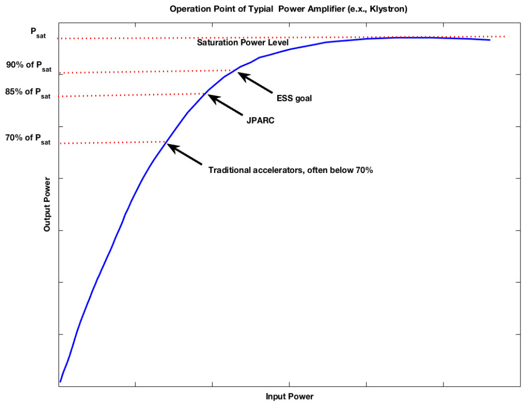

Figure 1: Operation points of klystron in closed loop in different facilities and ESS goal.

The higher efficiency point of power amplifiers we want to operate at, the more dynamic details we have to figure out for both cavity system and RF system. Dynamic detail identifications rely heavily on high precision measuring and characterizing basic cavity parameters (Q_L, R/Q, dynamic detuning, phase and amplitude) and system behaviours under beam-RF-cavity interactions. It

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is especially challenging to characterize these dynamics under varying operating points or environment. Advanced technologies in LLRF and ICS providing real time/online characterizing will be the key enablers for addressing such challenges. Real time calibration and online diagnostic system playing more and more important roles in modern technology, if applied appropriately, would be a very effective and innovative solution to these problems. Different real time/online calibration schemes will be introduced in this paper and discussion will be made to see how well they can be applied at ESS.

More development projects in LLRF system are also looking into the use of different techniques, such as feedback, predistortion and feedforward circuits. Both static and adaptive algorithms will be investigated. As the complete Linac at ESS will incorporate around 155 different RF sources, working at powers from 20 kW to 1.5 MW, a self-learning and adaptive system would minimise the commissioning time for the complete system.

AVAILABILITY

The goal of the availability of the ESS neutron source is 95%. In order to make this possible, the effort to enhance availability must be paid in every corner all over the design, construction, commissioning and operation stages. Two aspects of availability improvement is distinguished in this paper:

- Availability enhancement in system design and development. This includes careful design of overall system, careful selection of reliable components and product, and also possible inclusion of active or passive redundancy.
- Fault tolerance in operation. It acts more a strategy at the system level to mitigate failures that will occur inevitably in final commissioning and operation. One topic often mentioned for fault tolerance design, for example, is to have the possibility to run with one or more cavities in a detuned position when LLRF, Klystron or modulator get failure.

In early design and development stage, it is much easy to integrate availability improvement in design by considering redundancy and overall operation efficiency. For example, one design approach in LLRF system aimed for at the moment is to make use of a common hardware platform for all the LLRF systems and, as far as possible, also for the beam instrumentation systems. This will simplify service and reduce the cost of the necessary inventory of spare parts. The hardware will be built around an FPGA solution, which moves the adaptions to the different parts of the linac from hardware to software. As the FPGA makes it possible to both adjust the actual control layout, as well as the control parameters, to each individual system, any gains found in the development projects running in parallel to the industrial design of the hardware can be utilised. The additional cost of this solution is the necessity to have a very stringent version tracking system, in order to guarantee that each individual LLRF board has the correct code loaded that corresponds to its position in the Linac.

The need, if any, of redundant structures in the LLRF chain will be decided on the experience of other facilities, and on analysis of the prototype hardware. Even though there is not an inherent safety aspect of a high reliability, as in accelerator driven reactor, the goal of the ESS still sets a stringent demand on the hardware and software reliability.

Another important factor to improve availability is to well conditioning and testing individual system before integrating into the whole system with beam. After system design and development, knowledge and experience obtained in testing and conditioning individual system will be crucial to identify manufacturing imperfections and design flaws, to provide feedback on system production, and to develop strategies minimizing mistakes in integration to whole system. There is always larger failure rates in system start up and initial operation, and it costs much less to avoid overlapping this larger failure stage with the period of test and commissioning whole accelerator system with beam. For example, it would be advantageous to be able to run the LLRF system together with the control and timing systems without having to be fully powered up and having a beam in the accelerator. In order to make this possible, the LLRF systems will be designed so that they can be run on their own, with a simulated cavity and beam. This will make it possible to test the whole control system of the Linac before all the parts of the accelerator itself are in place. The model of the cavity and beam will either be implemented in the FPGA, or as a separate circuit connected to it. Both variants have different strengths and risks connected to them.

The possibility to also include simulated faults in these modules, such as Klystron degradation or modulator failure, will make it possible to test the contingency parts of the control system, and prepare the system for the high availability goal.

Availability enhancement is very important but trial and practical, more on system integration perspective to find a systematic solution to variety of problems, and it is hard to cover all in this paper. The following sections of this paper are thus mainly focusing the effort and possible solution to the second availability aspect fault-tolerance in operation, and introduce some general methods that are common to the solution enabling to improve energy efficiency.

Frequent appeared failures in RF and cavity systems showed in other facilities are cavity quench, field emission, software/hardware/configuration errors, the interlock trips of the arc, vacuum, reflection power and temperature, and the failures from klystron, modulators and other key RF components. The failures must be detected and fixed as fast as possible. If the failures cannot be fixed at once, they must be bypassed quickly so as that the system can get recovered as soon as possible. Under this context, insight into system dynamics under different operation conditions, instant online diagnostics for key system parameters and high degree of automated operation are highly required to support early detection of the faults and fast recovery from failures. For example, a

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cavity quench can be handled quickly by lowering the gradient of the troubled cavity in next RF pulse, if dynamic Q_L changes can be captured in real time; For the cavity/modulator/klystron failure, we could recovery the system either in a relatively short time by adjusting the adjacent cavities gradients and phases or by adjusting RF phases in all the downstream cavities, if system dynamics in different operation gradient/synchronous phase are well known in advance.

Most of systems are usually designed and optimized at certain nominal operating point, however, the final operation point in accelerator systems usually needs to be flexible enough to adjust away from design value. It requires also changing operation point quickly and correctly when it comes to the fault tolerance strategies where fast detection and fast recovery are essential. In this sense, similar with what we discussed in energy efficiency section, the higher availability of RF & Cavity system (with beam loading) to operate at, the more dynamic details needs to be identified, so as to have the abilities to work in different operation conditions and to change operation point quickly and correctly. The following sections describes thus more on what the system dynamics are and more how to figure out these dynamics [1].

CAVITY AND RF DYNMICS IDENTIFICATIONS

Dynamic details identifications rely very much on high precision measurement of basic cavity parameters (Q_L, R/Q, dynamic detuning, phase and amplitude) and RF system parameters (saturation curve, rising time, group delay, reflection and matching, etc), and consequent high quality data with high resolution, high precision and completeness.

While a variety of techniques become possible today for such high precision measurement thanks to the high performance hardware, how to calibrate these parameters at varying operating point due to system environment variations still challenging. Real time calibration and online calibration system playing more and more important roles in modern technology seems a very effective and innovative solution to this problem.

Cavity Dynamics in General

Some examples of general cavity dynamics are listed but not limited as follows:

- Cavity pass band modes
- Lorentz force detuning at different cavity field levels
- Lorentz force to cavity tuning transfer function
- Piezo tuner to cavity tuning transfer function (time domain, or frequency domain)
- Moto tuner to cavity tuning transfer function
- Microphonics spectrum
- System open loop matrix
- System closed loop matrix
- Cavity field behaviour close to and at quench
- Multipacting in cavity and power coupler
- Fast fault detection and fault recovery

Cavity Dynamics Online Identification

As mentioned earlier, dynamic details identifications rely very much on high precision and online measurement of basic cavity parameters: amplitude (accelerating cavity voltage)V_c, phase (synchronous phase) φ_b, loaded quality factor Q_L, cavity detuning $\Delta\omega$, and R/Q, which reflects the fundamental static and dynamic field behaviours of a RF powered cavity with beam loading [2]:

$$\frac{dV_{cav}}{dt}+\frac{\omega_0}{2Q_L}\left(1-i\tan\varphi_D\right)V_{cav}=\frac{\omega_0}{4}\left(R/Q\right)I \tag{1}$$

where $\tan\varphi_D$ is the detuning angle,

$$\tan\varphi_D=Q_L\left(\frac{\omega_0}{\omega}-\frac{\omega}{\omega_0}\right)\approx 2Q_L\frac{\Delta\omega}{\omega}$$

In steady state, V_{cav} reaches designed value V_c, and required generator current can be written as [2]:

$$I_{gr}=\frac{2V_c}{\left(R/Q\right)Q_L}+I_b\cos\varphi_b \tag{2}$$

$$I_{gi}=-\frac{2V_c}{\left(R/Q\right)Q_L}\tan\varphi_D-I_b\sin\varphi_b \tag{3}$$

These basic parameters are well discussed in literature but sometime defined in different ways. To make it consistent in this paper, the definitions of these parameters are explained. V_c is the absolute value of the line integral of the electric field seen by the beam along the accelerating axis, which reflects the maximum achievable energy gain for beam acceleration. φ_b is, for a given particle traversing the cavity, the phase shift from RF phase at which it obtain the maximum energy gain. It is equivalent to the phase angle between beam and accelerating voltage in vector diagram. Q_L is defined as 2π times the number of RF cycles needed for stored energy to dissipate on the wall and leak out the from couplers, which measures the 'quality' of cavity resonator, conveys the information of cavity field decay rate, and determines cavity bandwidth. $\Delta\omega$ becomes a key parameter in superconducting cavity due to long RF pulse (~3.5ms) operation along with high gradient level. R/Q relates the stored energy and maximum accelerating voltage acting on the beam, which depends on only the cavity shape for a given resonant mode. However, in proton machine, as the velocity of beam changes with its kinetic energy, even having the same cavity field, the accelerating voltage seen by the beam varies from cavity to cavity. Thus the R/Q has to be considered as R/Q (β) as it changes as beam velocity β varies along the linac [3].

Static coefficients of accelerating voltage V_c to probe power can be determined by phase scan methods, and dynamic voltage is then derived from real time probe power measurement. A high signal to noise ratio of probe power signal and high isolation to other measurement channel are critical to monitor accurately real time voltage variations. Some necessary filtering is also needed to rule out the pass-band mode effect. Power amplifier driv-

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ing current is determined by forward power, where high quality directional coupler with good directivity is essential to minimize mixed reflected power. High precision beam current measurement is another important factor. Beam current variations during pulse and from pulse to pulse must be taken into account and it is better to have it below certain value.

Having adequate and high quality measurement of cavity amplitude V_c, driving current and beam current, as well as timing of beam current, other dynamic parameters beam phase, R/Q, and Q_L can be derived from equation 1 with small enough sampling step and long enough sampling data. It is then able to formulate a linear least square problem for estimation of these parameters, which is described in the other paper in this conference.

For dynamic detuning and Q_L, another widely used and well-proved online diagnostic method in other facilities is worth considering. Derived from the same equation 1, dynamic $Q_L(t)$ and $\Delta\omega(t)$ can be written as:

$$\omega_{1/2}(t)=\frac{1}{2}\frac{d\left|V_{cav}\right|^2}{dt}\Big/\left(\left|V_{for}\right|^2-\left|V_{ref}\right|^2\right) \qquad (4)$$

$$\Delta\omega(t)=\mathrm{Im}\left(\frac{dV_{cav}}{dt}-2\omega_{1/2}(t)V_{for}\Big/V_{cav}\right) \qquad (5)$$

Where $\omega_{1/2}(t)=\omega_0(t)/2Q_L(t)$. Dynamic $Q_L(t)$ and $\Delta\omega(t)$ in this way are only related to probe power and forward power, affected probably less by the noise and perturbations. The precision of dynamic $Q_L(t)$ and $\Delta\omega(t)$ depends on how precise the measurement of cavity probe power, cavity forward power and reflected power can be. It is reported that better precision will be achieved if good isolation and correction of forward power and reflected power is made [4, 5].

RF Dynamics in General

Some examples of general cavity dynamics are listed but not limited as follows:

- Power amplifier input-output characteristics (power and phase) at different modulator voltage
- Modulator ripple frequency and amplitude
- Circulator characteristics (return loss, frequency) under different power consumption, different reflection power, and working temperature
- Power amplifier bandwidth variation at different output power level
- Driver amplifier and power amplifier delay, rise time and falling time under different power level
- Phase drift in cables due to temperature or humidity changes

RF Dynamics Online Identification

Benefit from advanced hardware platform and one power amplifier (or two in spoke section) for one cavity system configuration, there are enough RF measurement channels around driver amplifier, before and after power amplifier, as well as around circulator. There is therefore good opportunity to carry out elaborate experimentation and make accurate measurement on individual RF components, and obtain adequate data with high resolution and high accuracy. With good quality of data and complete information of system, similar least square estimation method as mentioned in online cavity dynamic diagnostic would be applicable as well to estimate the real time RF system parameters, thereby giving online diagnostics for RF dynamics.

Another simpler method for online RF dynamic diagnostics would be also interesting. In this method, instead of using a pure pulse shape, appropriate RF input waveform with exponential slop or linear slop in cavity filling time is chosen to feed the klystron, in order to generate all power levels from zero to full power. By measuring RF powers before and after driver amplifier, klystron, and circulator, online characteristics of system dynamic such as nonlinearities, return loss and bandwidth variations would be obtainable. 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.

ITERATIVE LEARNING FROM PRACTICE AND MODELLING

As analysed above, online system dynamic seems feasible and promising to address the challenges to achieve higher efficiency and availability, with big benefit from advanced technologies.

However, while algorithm and measurement methodology works ideally with the ideal cavity system, it is generally not possible to get a perfect response in reality, due to the uncertainties and errors such as fabrication errors, installation errors, measurement errors, random noises, feedback system transient responses, system environment variations and operation condition variations. Under these cases, the measurement and even the algorithms expect to be adjustable to maintain the required performances.

Further more, wide spread of cavity parameters make it impossible to employ a single “uniform’ control algorithm and control configuration data even for the same type of the cavities. Instead, adjustments and modifications are needed for each cavity and customized approaches are preferred to reflect cavity’s individual performance and characteristics. Under this context, a large number of data are expected and required for all the cavity systems in ESS linac. A controlled, centralized and searchable database is therefore necessary to save the data effectively and ensure to obtain the data immediately when using them.

When preparing to collect data, it is important to keep in mind which kinds of data are required, and to what extent the data quality should be. Although it is the best way to verify the data and refine the requirements in the normal operating cavities, it is always not practical and too late to generate requirements at final stage. Instead, the data and general data quality required could be estimated earlier from results of test stands or similar cavity

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tests in other accelerator facilities, as well as the prediction of theory models. As an example, the time-domain transfer function data of piezo tuner to cavity detuning would be required to compensate the longer pulse Lorentz force detuning, according to the experiments carried out at Fermilab. Another example is that, the data resolution of better than 100ns can be concluded from theory model prediction for feedforward table to compensate beam-loading effects in normal conducting cavities.

Due to uncertainties in reality, practice (experiment and data) is always different from what predict in theory or model, however, models do provide us a framework for expressing such uncertainty in a precise, quantitative and controlled way, allowing us to exploit this to control individual variables and to make predictions that are optimal according to appropriate criteria. It contributes a lot for system development if we can learn from practice, and reviews the practice with theory/model predictions.

A quick and effective way to combine practice (data, experiment) and model/theory might be as follows:

- Build realistic models (measured transfer functions or high order mathematical models) or modify parameters of existing theory models, based on measured data from specific experiments.
- Adjust parameter values and table values, to obtain "ideal" configuration data for the models. This is achieved by judging if the model predict responses meet design requirement.
- Apply these "ideal" configuration data in real cavity system at test stand or other place available, and measure the response of each sub-system such as klystron-modulate, piezo tuner, motor tuner, and Lorentz force detuning. Elaborate and careful design of experiments for the excitation signals, measure techniques and data processing, are essential here to obtain required response from subsystem under measurement, while isolate or filter responses and cross-talk from other subsystems.
- Check if the measured response meets the design requirements. If not, try to identify the errors in model simulation by studying the effect produced by suspected errors. Correct errors when finding them.
- If the errors cannot be fixed, modify or improve the model to better reflect the effect of errors. Then repeat the second step, to obtain an "optimal" configuration data.
- Repeat or partly repeat above steps if necessary.
- Residual errors will be dealt with adjustable algorithm, which is also useful for the variations of environment and operation conditions.

In this way, the models and "optimal" configuration data will be more realistic and get matured through the process of prototype, test and series production. The cavity system can be much better understand as well. As a result, a more sophisticated system will be available in beam commissioning and normal operating phase so as to be able to operate the cavity system more effectively and efficiently.

In steps above, it is can be seen how an iterative learn process works from practice (data and RF experiments) and from theoretical analysis (model). Test/experiments, data, and models are not independent, but interact with each other for a better system development, which can be seen more clearly in Figure 2.

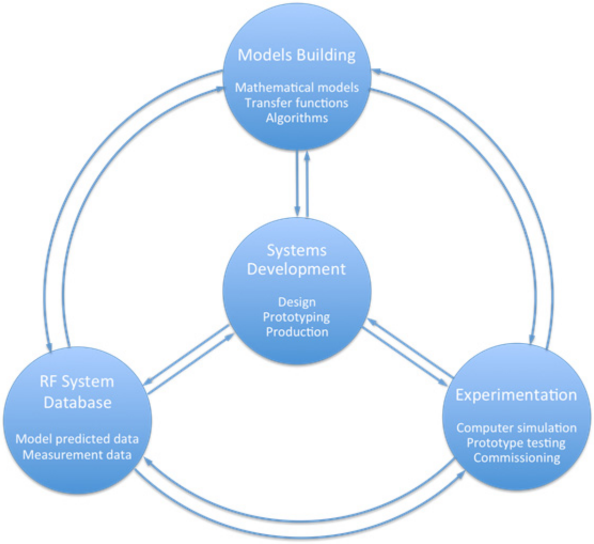

Figure 2: Different RF input waveform to make online RF dynamic diagnostics.

CONCLUSION

Increasing attention has been paid in accelerator for higher energy efficiency and higher availability, with the background of larger and larger scale of accelerator facility emerges. With the advent of advanced technology, it becomes promising to make online diagnostics of key system parameters and thus to gain insight to the system dynamics that was always viewed as black box, which are crucial to improve energy efficiency and availability.

However, to be successful, the deployment of these technologies must be embedded within local conditions taking into account available resources, existing hardware/software structures and operation modes. In spite of the complexity of system, it makes always sense to learn from practice, carrying out experiments, obtaining adequate high quality data, and then verified or guided in model or theoretical framework.

It is important to keep in mind challenges and tough facts expected to face during the phases of commissioning, normally operating and maintaining. It is equally important, if not more, to identify and find suitable solutions to address these challenges, and to understand better system dynamics and get to know its limitations, thereby testing, controlling and operating the system efficiently and effectively.

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