APPLICATION INVESTIGATION OF HIGH PRECISION MEASUREMENT FOR BASIC CAVITY PARAMETERS AT ESS

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Abstract

The ESS cavity control and operation methods/algorithms are challenging due to the use of long pulse, higher beam intensity, high beam power, high gradient, uncertainties in spoke cavities and high demands for energy efficiency and availability. Suitable and effective solutions could make use of modern technologies (flexible FPGA, faster CPU, bigger memory, faster communication speed, etc.), novel measuring techniques, accurate system modelling, and advanced control concept. Those possible implementations are essential to a better understanding, and thus a better operation of ESS cavity especially SRF cavities. All these concepts rely on high precision measurement of basic cavity parameters and consequent high quality data with high resolution, high precision and completeness. This paper focuses on how high precision measurement will address the challenges at ESS on the following topics: long pulse Lorentz force detuning, high precision phase and amplitude setting, heavy beam loading compensation and power overhead reduction.

INTRODUCTION

Cavity parameters discussed in this paper refer to the parameters in cavity baseband equation that reflects the fundamental static and dynamic field behaviours of a RF powered cavity with beam loading [1]:

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

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]:

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

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

Five basic parameters are being discussed in this paper: accelerating cavity voltage V_c, synchronous phase φ_b, loaded quality factor Q_L, cavity detuning $\Delta\omega$, and R/Q.

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 [3].

CAVITY DETUNING ΔΩ AND LOADED QUALITY FACTOR Q_L

Measurement/Calibration Method

While high precision measurement of single point Q_L and $\Delta\omega$ can be done by measuring decay of the cavity field, dynamic $Q_L(t)$ and $\Delta\omega(t)$ can be derived from the cavity base band differential equation (1) [4, 5]:

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

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

Where $\omega_{1/2}\left(t\right)=\omega_0\left(t\right)/2Q_L\left(t\right)$. 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 [4, 5] that better precision will be achieved if good isolation and correction of forward power and reflected power is made.

Adaptive Lorentz Force Detuning Compensation

The adaptive Lorentz force detuning compensation algorithm via piezo tuner has been developed at Fermilab to compensate for Lorentz force detuning in SRF cavities, which is promising to address the challenge of long pulse Lorentz force detuning compensation. Appropriate piezo tuner compensation waveform is automatically generated in this method, by inverting cavity response matrix obtained by applying elaborately designed stimulus signals on piezo tuner. Precisely determining the Q_L and the $\Delta\omega$ is essential in this method to acquire accurate result [5].

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Quench Detection

Unloaded quality factor Q_0 drops significantly when quench occurs, but it is unable to measure directly. Instead, the drop in Q_L indicating Q_0 change is measured for quench detection. Precise Q_L measurement is therefore essential for any quench detection algorithms [6].

Residual Detuning Compensation

Residual detuning compensation is needed when cavity detuning is not fixed completely by piezo tuner, which is then usually done by feedback or adaptive feed forward. For ESS spoke cavities with relatively big cavity bandwidth (~1.2 kHz) and relatively low gradient (9.0 MV/m), cavity detuning compensation could be accomplished without piezo tuners, as only 1% power overhead is required to compensate detuning up to 1/5 cavity bandwidth (~240Hz). The compensation in this case is mainly to deal with phase distortion caused by detuning (~22° for 1/5 cavity bandwidth detuning).

A simple detuning compensation method is investigated with the assumption of high precise measurement for detuning available. The principal is measure the detuning from cavity in current pulse, and meantime generate required feedforward signal by equation (2) and (3), and then apply this generated FF signal to the next pulse. One iteration is just required if detuning information for FF learning is derived from constant cavity field, but it is the usual case in normal operation. If that is the case, more iterations are required to get constant cavity field.

This method is sensitive to inaccurate measurement of detuning caused by hardware limitation (such as directional directivity, directional coupling factor), which is shown in Figure 1.

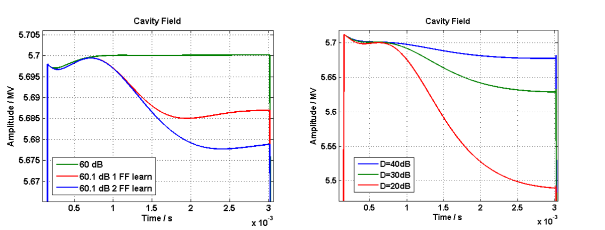

Figure 1: Sensitivity of feedforward method to coupling factor (left) and directivity (right)

ACCELERATING VOLTAGE V_C AND SYNCHRONOUS PHASE Φ_B

Measurement/Calibration Method

Most common ways to calibrate proton linac phase φ_b and accelerating voltage V_c are Phase scan methods. They are referring here to the ways of calibrating setting point for RF cavities by scanning RF phase and amplitude, measuring beam arrival times at downstream locations (usually at two BPMs), comparing measured phase and amplitude to model predicted values, and identifying the best-matched data for calibration. The experience at SNS and JPARC indicate 1°, 1% accuracy in phase and voltage can be achieved in low energy linac part. However, accuracy of phase scan method up to 2°, 2% or even worse could be expected in high energy part due to insensitivity of high-velocity proton beam to energy gain in cavity [7]. In RF based calibration method, 5% or even worse is expected according to experience in other labs.

Beam Energy Spread and Beam Quality

Calibration errors in accelerating voltage and synchronous phase lead to beam energy spread, phase deviations and longitudinal emittance growth, which cause beam quality degradation. While beam energy spread and phase deviation is believed to be a static systematic error and could be mitigated to some extent by adjusting RF power fed to cavity, longitudinal emittance growth cannot be corrected in this way [8]. Calibration errors for accelerating voltage and synchronous phase are required to maintain within ±1°, ±1% for the whole linac. Great attention and investigation has to be paid to reduce calibration errors.

Reference for System Calibration

Precisely calibrated accelerating voltage and synchronous phase would be the reference for other parameter estimation and system calibration, as they reflect the quantities seen by beam and are the ultimate goal for beam acceleration. On the other hand, perfect calibration to 'true value' without considering beam is meaningless, since there are no 'true parameters'. Therefore, instead of calibrating other parameters to their meaningless "true value", converging these calibrations to quantities seen by beam seems more practical.

Power Overhead Reduction

Optimized parameters like Q_L, pre-detuning, injection time are no longer optimal under calibration errors. As a result, cavity response deviates the design value at the beginning of beam injection in feedforward mode, as shown in Figure 2. Big overshoot then follows when closing feedback control loop, which is one of the reason to keep adequate power overhead away from klystron saturation. Re-adjustment has to be done in order to get a constant field in feedforward mode by pre-detuning value and beam injection time. The adjustment resolution of pre-detuning and injection time determines how good the field flatness can be.

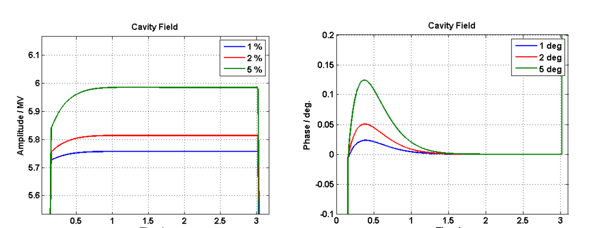

Figure 2: Amplitude (left) and phase (right) deviations at the beginning of pulse due to calibration errors

The other way to solve this overshoot issue is to inject beam at later steady-state stage at price of reduced power efficiency, adding corresponding feedforward signal to compensate beam loading.

R/Q

Measurement/Calibration Method

A direct way to determine R/Q is the "bead pulling" field profile measuring method, by monitoring π-mode frequency offset when perturbing cavity field using a small metal bead. This method is suitable for offline measurement but not for operation [3].

An alternative method to calibrate R/Q could make use of voltage induced by a short beam or RF pulse. For the very short pulses T_B ($T_B \ll 1/\omega_{1/2}$, TB<<$1/\Delta\omega$, $\omega_{1/2}$ is the cavity half bandwidth), the maximum value that RF or beam pulse induced voltage reaches can be approximately written as [9]:

$$V_{\max} \approx \frac{\omega_0}{4}(R/Q)T_B \cdot I \tag{6}$$

By measuring voltages induced by short pulses with different currents and using linear regression, R/Q could be determined.

Phase and Voltage Calibration

As mentioned in accelerating voltage Vc and synchronous phase φ_b calibration, the accuracy of phase scan for V_c and φ_b calibration can achieve 1°, and 1% in low energy part, but struggle to achieve this value in high energy part. The alternative way to setting phase and amplitude is transient beam loading based method, which determines the phase and amplitude calibration coefficient by comparing measured beam induced voltage with model predict value.

It is promising to achieve high accuracy if high precision measurement can be fulfilled. Once R/Q can be calibrated correctly, model predict beam induced voltage will reflect more correctly the real value, and hopefully to get a more accurate calibration coefficient. Here the R/Q has to be considered as R/Q (β) as it changes in different cavities where beam velocity varies.

Beam Loading Compensation

Heavy beam load (62.5mA peak current) is expected in ESS cavities, which results in potential problems of power overshoot issue in superconducting cavity control and field control issue in normal conducting cavity control. The effective solution to these issues is to apply feedforward compensation for each beam mode. The beam pulse parameters (arrive time, pulse length, and peak current) is essential to make effective compensation, while among these, to determine proton beam arriving time is critical since pulse length and peak current can be sent via timing system in advance.

Measuring correctly the beam-induced voltage as mentioned in equation (6) seems one promising way to determine the beam arrival time. Preliminary measurement could be done in feedforward mode in beam commissioning dealing with different beam modes, while online measurement could be done in normal operation mode dealing with system environment variations.

Exception Handling and Fault Recovery

Correct online beam induced voltage measurement as mentioned above and consequent beam parameters identification can also applied for exception handling. For example, a beam pulse missing can be detected in time by this method, and adjust corresponding control parameters immediately to prevent cavity field rising too high. Appropriate actions can be made this way so as to recover fast from faults and avoid triggering unnecessary interlocks.

SUMMARY

High precision measurement is essential to understand the cavity system and to develop advanced methods and algorithms to address the challenges at ESS. The combination and interaction of data, model and tests/experiments will make great contribution to better system development.

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