TRANSIENT BEAM LOADING BASED CALIBRATION FOR CAVITY PHASE AND AMPLITUDE SETTING

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Abstract

Traditional phase scan method for cavity phase and amplitude setting is offline and hard to track the variations of environment and operation points. An alternative beam loading based calibration method is investigated in this paper, which might become useful online/real time calibration method.

INTRODUCTION

Setting correctly phase and amplitude for accelerating cavity is crucial in beam commissioning and beam operation. The phase refers here the synchronous phase which is defined as, 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. The amplitude refers here the cavity voltage, which is defined as 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.

This paper introduce some general methods used for phase and amplitude setting in different accelerators, analyse the advantage and disadvantage of theses methods, and then discuss an online beam based calibration method which seems promising and very suitable to be employed at ESS.

PHASE SCAN

Phase scan methods are referring here to the way of calibrating setting point for RF cavities by scanning RF phase and amplitude, measuring beam arrival times at down-stream locations, comparing measured phase to model predicted data, and identifying the best-matched data for calibration.

ΔT-method

The ΔT-method is a classical phase scan method and used widely in normal conducting linac such as in LAMPF, Fermilab, JPARC and SNS. Linear system response is assumed in ΔT-method and it is only valid in the vicinity of design phase and amplitude. ΔT-method is a cavity-by cavity operation, assuming that the cavities upstream to the one being adjusted are "on", and the cavities downstream are "off". Beam phases (or beam arrival time) are provided by two downstream BPMs. The two BPMs can be neighbouring each other, or separated by several cryo-modules, which depends on the specific location of cavity (the sensitivity of beam velocity to energy gain becomes low as beam energy goes high) being adjusted. The cavities between two BPMs are usually detuned more than 10 cavity bandwidth.

The general procedures of the ΔT-method are listed below [1, 2]:

- Find approximate phase and amplitude set point, by observing BPM signals and beam loading effect, and doing RF based calibration.
- Cavity being adjusted is off. Record two downstream BPMs phases $\phi_{\text{bpm1-0}}$ and $\phi_{\text{bpm2-0}}$.
- Ramp the cavity being adjusted to nominal field calibrated by RF power based measurement (amplitude accuracy in RF based calibration is around 10%).
- Turn on beam with low repetition rate, low beam intensity and low beam pulse length.
- Record two downstream BPMs phases ϕ_{bpm1} and ϕ_{bpm2}.
- Calculate relative changes of BPMs phases between cavity "on" and "off" $\Delta\phi_{\text{bpm1}} = \phi_{\text{bpm1-0}} - \phi_{\text{bpm1}}$ and $\Delta\phi_{\text{bpm2}} = \phi_{\text{bpm2-0}} - \phi_{\text{bpm2}}$. Plot $\Delta\phi_{\text{bpm1}}$ and $\Delta\phi_{\text{bpm2}}$.
- Scan the cavity RF phase with certain phase step (for example 0.5°) over the certain range (for example, ±5°) of design phase, and repeat above procedures at each phase step, to generate a constant-amplitude, variable-phase curve in $(\Delta\phi_{\text{bpm1}}, \Delta\phi_{\text{bpm1}})$ plane.
- Calculate the slope of the curve, which depends on cavity amplitude, and compare it with the slope values of model predict curves at different amplitude. These predicted curves have a common point of intersection.
- Use some fitting algorithm to determine best-fit amplitude.
- Having determined proper amplitude, it is now possible in model to calculate the transfer function relating $\Delta\phi_{\text{bpm1}}$ and $\Delta\phi_{\text{bpm2}}$ to phase deviation $\Delta\phi$ and energy deviation ΔW at the entrance of cavity with respect to nominal value. $\Delta\phi$ and ΔW can then be determined.
- Correct the phase set point, and if necessary, correct as well the input energy at cavity entrance according to the result in last step.

Signature Matching

Unlike the ΔT-method having a linear system response and small input energy displacement restriction, signature matching method can work at large displacement of initial conditions. In high energy part, signature matching methods can easily scan the phase over 360° at different amplitude, and make good match with model predict curve. However, at low energy linac, cavity phase scan can only be several ten degrees where beam stay sufficiently bunched to produce good signals at downstream BPMs, and the accuracy indicated at SNS for low energy part is not good enough. ΔT-method is probably necessary to get a good setting ac-

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ISBN 978-3-95450-178-6

curacy for ESS spoke cavities. The general procedures for signature matching are listed below [3]:

- Ramp the cavity being adjusted to nominal field calibrated by RF power based measurement (amplitude accuracy in RF based calibration is around 10
- Detune the downstream cavities by more than 10 cavity bandwidth to bypass the beam, which locate between two downstream BPMs.
- Turn on beam with low repetition rate, low beam intensity and low beam pulse length Record two downstream BPMs phases ϕ_{bpm2} and ϕ_{bpm2}.
- Record two downstream BPMs phases ϕ_{bpm1} and ϕ_{bpm2}.
- Scan the cavity RF phase with certain phase step (for example, 0.5°) over the full range 360°, and repeat last step at each phase step, to generate a constant-amplitude, variable-phase curve in ($\Delta\phi_{\text{bpm1}}$, $\Delta\phi_{\text{bpm2}}$) plane.
- Predict the values in model for BPM phases ($\Delta\phi_{\text{bpm1-calc}}$ and $\Delta\phi_{\text{bpm2-calc}}$) as a function of synchronous phase.
- Spline fit the measured phase difference ($\phi_{\text{bpm1}} - \phi_{\text{bpm2}}$).
- Match the model predict values with measured ones, by minimizing the difference between ($\phi_{\text{bpm1}} - \phi_{\text{bpm2}}$) and ($\phi_{\text{bpm2-calc}} - \phi_{\text{bpm1-calc}}$) over the range of scanned phase. Phase deviation $\Delta\phi$, input beam energy deviation at entrance of cavity ΔW, and cavity amplitude deviation ΔV are adjusted in this matching procedure.
- Correct the phase and amplitude set points according to the result in last step.

TRANSIENT BEAM LOADING METHOD

Drift Beam Method

The drifting beam technique is based on very strong beam-cavity interactions in the SC cavity for high current beams. It was proposed several years ago and recently realized at SNS. It uses measured beam currents and pulse shapes with a beam current monitor (BCM), and beam induced signals in the SC cavity with the cavity control circuit. Using the measured beam current in a beam-cavity model that simulates the beam-loading in the cavity, by comparing model simulation results with the actual measurement of the cavity, cavity phase and the field amplitude are determined precisely. The general procedures are listed below [4]:

- Measure the beam current and beam pulse shape by BCMs.
- Tune the cavity as close ass possible to resonance.
- Turn off RF. Turn on beam with low repetition rate 1Hz, low beam intensity 10mA, and low beam pulse length.
- Measure the phase and amplitude of beam-induced signal.
- Measure the phase and amplitude of noise signal before next beam pulse coming. Subtract noise signal from beam-induced signal.
- Repeat the measurement in last step for ~10 beam pulses and average the results.
- Predict the beam-induced signal in model by measured beam current and beam pulse shape.
- Determine the phase offset and amplitude calibration coefficient by comparing measured result with model calculations.
- Set amplitude and phase.

COMPARISON BETWEEN PHASE SCAN AND DRIFT BEAM METHOD

By reviewing the literature of different method at SNS for phase and amplitude setting and collecting all parameters used for such setting, it is worthwhile to compare the different between different methods. To make it consistent, only the results from the same facility (SNS) are used for comparison. As this paper is focusing on superconducting cavities, only the methods used in superconducting cavities such as signature matching and drift beam method are chosen. However, it should be noted that, due to superconducting linac at ESS covers also low energy part, the method used for normal-conducting cavities at SNS like ΔT-method might be necessary for ESS.

Table 1: Key Performance and Parameter Comparison Between Phase Scan and Transient Beam Method

Accuracy and parameter used	**Phase scan – signature matching**	**Transient beam loading – drift beam**
Amplitude	±2.4%	±4%
Phase	±1°	±1°
Pulse length	<20 µs	>50 µs
Beam current	<20 mA	<20 mA
Rep. Rate	1 Hz	1 Hz

As shown in Table 1, both phase scan and transient beam loading methods can achieve good phase accuracy up to ±1°. To achieve a good accuracy, phase scan method requires as low beam loading as possible to not disturb the cavity field, while drift beam method requires a relatively stronger beam loading in cavity to get a strong beam induced voltage to suppress noise. The signal to noise ratio is often low in drift beam method at SNS, due to short beam pulsed length and low beam current, which is usually the case in early stage of beam commissioning to avoid damage to other hardware or beam dump.

IMPROVED TRANSIENT BEAM LOADING METHOD AT DESY

One of the main problem of drift beam method is poor signal to noise ratio (SNR) due to limited beam loading in beam commissioning. SNR is sometime less than 10, indicated by some measurement at SNS, which is probably one of the limitations to achieve higher and stable accuracy.

Suffering less from poor SNR like drift beam method at SNS, the transient beam loading based method for phase and amplitude setting used at DESY tried to improve SNR a lot with benefit from high performance hardware and works well now for FLASH and will most probably used in XFEL.

ISBN 978-3-95450-178-6

The main difference in method used at DESY from drift beam method is, instead of un-powering the cavity before beam drifting through, a constant driving power is first fed into the cavity to build up the cavity field up to operating gradient [5], and then the beam goes through the cavity, as shown in Figure 1. The drop of cavity voltage caused by beam loading is calculated by comparing two measured cavity voltage, one measured before beam coming, and the other one measured after beam coming. Higher SNR is ensured and high resolution of beam transient loading can be observed, thereby giving high quality information to calibrate the phase and amplitude of cavity field.

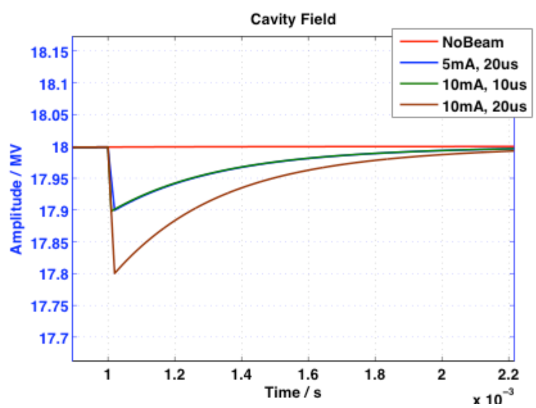

Figure 1: Schematic view of transient beam loading method used at DESY (ESS cavity parameters are used).

AN ALTERNATIVE ONLINE BEAM BASED CALIBRATION METHOD

The procedures for phase and amplitude setting used at DESY requires special operating conditions (open loop, two separated measurement, etc) and cannot thus be used in normal operation when the cavity is running in feedback mode and adaptive feed-forward mode with heavy beam loading. Considering big advantages at ESS for such online beam based calibration: heavy beam loading (62.5mA compared with 9mA in FLASH or XFEL) and 1 power amplifier per cavity (1 power amplify for 8 cavities in FLASH, and for 32 cavities in XFEL), an online beam transient based calibration method is thus investigated at ESS.

Our starting point is the equation [6]

$$\dot{\mathbf{V}}(t) = (-\omega_{1/2} + i\Delta\omega(t))\,\mathbf{V}(t) + \kappa_g \mathbf{I_g}(t) + \kappa_b \mathbf{I_b}(t) \quad (1)$$

which describes the time evolution of the cavity voltage in the baseband[1] (we only consider the dynamics of the fundamental mode). Bold symbols denote complex quantities.

The measured cavity voltage is given by

$$\mathbf{V}_{\mathrm{m}}(t) = \mathbf{V}(t) + v(t) + \sum_k \mathbf{V}_k(t),$$

where $v(t)$ is measurement noise and the sum corresponds to interference from parasitic modes.

Also, the generator current $\mathbf{I_g}$ is not directly measured, but rather a quantity $\breve{\mathbf{I}}_{\mathrm{g}}$ proportional to it is measured by the directional coupler downstream the amplifier, i.e., $\breve{\mathbf{I}}_{\mathrm{g}} = \mathbf{k}\mathbf{I_g}$ for some complex $\mathbf{k}$.

Least Squares Estimation

From measurements of $\mathbf{V}_{\mathrm{m}}(t)$ and $\breve{\mathbf{I}}_{\mathrm{g}}(t)$, as well as the timing of the beam pulse, we can formulate a linear least squares problem for estimation of the beam phase.

Let the time-derivative of $\mathbf{V}_{\mathrm{m}}$ (computed as a first order difference), be the response variable

$$\mathbf{y} = \begin{bmatrix} \dot{\mathbf{V}}_{\mathrm{m}}(t_1) & \dot{\mathbf{V}}_{\mathrm{m}}(t_2) & \dots & \dot{\mathbf{V}}_{\mathrm{m}}(t_N) \end{bmatrix}$$

and let the measured terms in the time derivative of $\mathbf{V}_{\mathrm{m}}$ form the regressor matrix,

$$\mathbf{X} = \begin{bmatrix} \mathbf{V}_{\mathrm{m}}(t_1) & t_1\mathbf{V}_{\mathrm{m}}(t_1) & \breve{\mathbf{I}}_{\mathrm{g}}(t_1) & \Gamma(t_1) \\ \mathbf{V}_{\mathrm{m}}(t_2) & t_2\mathbf{V}_{\mathrm{m}}(t_2) & \breve{\mathbf{I}}_{\mathrm{g}}(t_2) & \Gamma(t_2) \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{V}_{\mathrm{m}}(t_N) & t_N\mathbf{V}_{\mathrm{m}}(t_N) & \breve{\mathbf{I}}_{\mathrm{g}}(t_N) & \Gamma(t_N) \end{bmatrix}$$

where

$$\Gamma(t_k) = \begin{cases} 0 & t_k \text{ before beam start} \\ 1 & t_k \text{ after beam start} \end{cases}.$$

Then the relation

$$\mathbf{y} = \mathbf{X}\boldsymbol{\theta}$$

is approximately satisfied for some parameter vector

$$\boldsymbol{\theta} = \begin{bmatrix} \boldsymbol{\theta}_1 & \boldsymbol{\theta}_2 & \boldsymbol{\theta}_3 & \boldsymbol{\theta}_4 \end{bmatrix}^T,$$

where $\angle\boldsymbol{\theta}_4$ is the beam phase that we are looking for.

The least squares estimate of $\boldsymbol{\theta}$ is given by

$$\boldsymbol{\theta}_{\mathrm{LS}} = (\mathbf{X}^*\mathbf{X})^{-1}\mathbf{X}^*\mathbf{y}.$$

Note that time-variation of the detuning is handled by the term $\boldsymbol{\theta}_2$, which corresponds to $\mathrm{d}(\omega_{1/2} + i\Delta\omega)/\,\mathrm{d}t$.

If there is significant interference from passband modes, their effect will be greatly amplified in $\dot{\mathbf{V}}_{\mathrm{m}}$, degrading estimation performance. This issue is well mitigated by filtering the observed data, including $\Gamma(t)$, through a lowpass filter with sufficient rejection the passband modes.

We have only given an overview of a possible improved beam phase estimation procedure. Some possible modifications for an actual implementation are mentioned below.

- If there is some uncertainty about the start of the beam pulse, the corresponding samples can be left out of the estimation problem.
- If some parameters in (1) are known with high accuracy, this information is easily incorporated into the estimation problem.
- If it is certain that the $\omega_{1/2}$ does not change during the pulse, the problem can be formulated so that the estimated parameter θ_2 is purely imaginary.

[1] In [6] expressions are given for κ_g and κ_b, however these are not important in this context.

ISBN 978-3-95450-178-6

Numerical simulations show the proposed model to be quite robust. Note that measurements must be taken both with and without beam. Also the interval $[t_1, t_N]$ should be sufficiently short that the detuning can be considered linear.

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ISBN 978-3-95450-178-6