ON-LINE RF AMPLITUDE AND PHASE CALIBRATION

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Abstract

The paper shows how to extract the RF-beam calibration from RF signals during normal operating condition (when RF feed-back, beam loading compensation, learning feed-forward etc. are active). All the algorithms and computations were performed on signals recorded at FLASH accelerator but the main idea is general and can be used at other locations as well. It can be fully automated and used to track calibration changes.

INTRODUCTION

The accelerating RF field has crucial importance on the beam properties. It is not only used just to accelerate particles but also to shape the bunches at bunch compressors and therefore precise field regulation is a must. It is really important to control and measure the field as seen by the beam while usually only indirect (not using the beam) field measurements are available. Commonly the cavity field probes are used. Since they measure the field around the probe and not the field seen by the beam the measurements must be always referenced to the beam. Additionally, the probe signal as measured by the control system is affected by several other contributions like cable attenuation and phase shift, characteristics of downconverters, etc. The same concerns other cavity signals (V_{for} - forward and V_{ref} - reflected powers).

The beam is sampled through toroid signals. They give only the magnitude of the beam current (or rather bunch charge Q). All the RF signals should be referenced to the beam phase, with $\phi = 0$ corresponding to on-crest conditions.

Due to the cost reason, in numerous RF accelerators single RF source (e.g. klystron) is used to drive multiple cavities. The RF fields in individual cavities are probed and then added to build the total vector sum. The goal of the control system in such a case is to regulate the vector sum of cavities fields rather than RF field in individual cavities. In a case of vector sum control the phase and amplitude errors of the individual cavity field signals even with the perfect control result in a contribution to the energy spread in presence of microphonic noise [1]. Finite errors in the gradient and phase calibration of each cavity probe signal will result in a discrepancy between the vector-sum as seen by the accelerated beam, and the measured vector-sum which is stabilized by the RF control system.

The beam-RF calibration can be achieved by energy gain measurements. This is the direct way but requires special operating conditions, especially for vector sum control.

Another calibration method uses reverse action and measures the field transients generated at cavity by the beam. This method is especially convenient for vector sum control system. It allows calibrating individual cavities in relation to each other. Then absolute energy gain for the whole vector sum can be measured and final calibration made. Since this method measures relatively small transients made by beam all other sources affecting cavity field should be stable. That concerns in particular forward power. The consequence is the cavity field cannot be actively regulated during measurements. That excludes normal operating conditions of the machine.

This paper proposes a new method allowing to calibrate RF field to the beam possible to use during normal operating condition, in particular in feedback mode of controller operation. Instead of measuring beam transients it fits the beam to the cavity equation and estimate beam calibration.

MATHEMATICAL CAVITY MODEL

The well-known differential equation (1) describes the cavity behavior under RF drive and beam load conditions.

$$\frac{dV}{dt} + (\omega_{12} - i\Delta\omega)V - 2\omega_{12}(V_{for} + V_b) = 0 \qquad (1)$$

where: V - cavity voltage (complex); $V_{for} = R_L I_{for}$ - generator (RF source) induced voltage (complex); I_{for} - generator current (complex); R_L - loaded shunt impedance; $V_b = c_b|V_b|$ - beam induced voltage (complex)

One have to note that equation (1) is written for envelope of RF signals. It bounds RF signals (V, V_{for}) with the beam through constant half-bandwidth ω_{12} (depends on cavity geometry) and detuning $\Delta\omega$ (changes over pulse due to Lorentz Force Detuning).

The beam related component V_b in (1) requires additional discussion. It is an envelope of beam representation at RF frequency. It corresponds to the voltage response caused by the beam current I_b (the same way as V_{for} corresponds to I_{for}). Usually, the beam current is modeled as a train of gaussian-shape bunches of charge Q [1]. In such a case the RF frequency envelope of beam current one can obtain by its Fourier transform filtered out through the resonance characteristics of the cavity. Assuming the bunch length is much lower than bunch repetition period T_b and $\omega_{12} << \omega_0$ one obtains the simple result (2).

$$|V_b| = 2R_L\frac{Q}{T_b} = 2R_L I_{b0} \qquad (2)$$

where: Q - single bunch charge (measured by toroid); I_{b0} - DC component of beam current

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ISBN 978-3-95450-182-3

Concluding, fitting the beam to the cavity equation requires calibrated V_{for}, knowledge of ω_{12} (can be measured from the decay phase) and the detuning waveform over the pulse.

CALIBRATION OF FORWARD VOLTAGE

The cavity and forward voltage (generator induced voltage) can be calibrated using the relationship between cavity voltage and forward and reflected voltages (3).

$$V = V_{for} + V_{ref} \tag{3}$$

Fitting this equation one can obtain calibration factor for V_{for}. Unfortunately, the forward and reflected signal are sampled through non-ideal directional couplers and some crosstalks are visible between them two. The crosstalks can be taken into account with additional observations:

- during decay, the measured V_{for} comes only from crosstalk from V_{ref} (there is no drive).
- during the first phase of filling, when V is negligible, the field gradient is related to the V_{for} through ω_{12} (4).

$$\frac{dV}{dt} = 2\omega_{12} V_{for} \tag{4}$$

Using this additional information one can calculate the complex coefficients a, b, c, d that fit the equations (5) thus calibrate measured RF signals ($\hat{V}, \hat{V}_{for}, \hat{V}_{ref}$).

$$\begin{aligned} V_{for} &= a\hat{V}_{for} + b\hat{V}_{ref} \\ V_{ref} &= c\hat{V}_{for} + d\hat{V}_{ref} \\ V = \hat{V} &= V_{for} + V_{ref} \end{aligned} \tag{5}$$

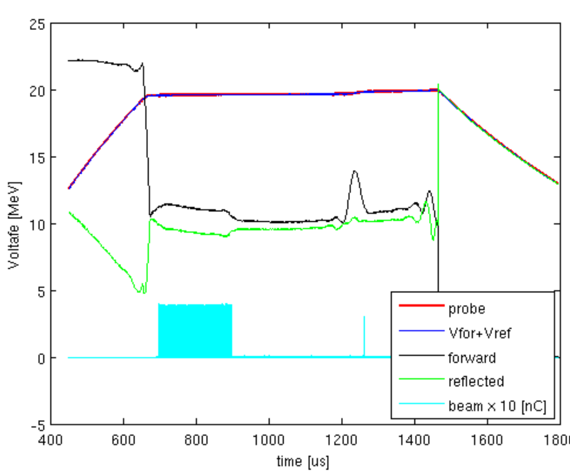

Figure 1: Calibrated forward and reflected voltages at cav.1 ACC1 at FLASH. Additionally the FLASH1 and FLASH2 beams are shown for reference.

The figure 1 shows (for one of the several analyzed cases) the cavity RF signals after applied calibration procedure. Both measured and calculated ($V_{for} + V_{ref}$) cavity voltage fits well indicating good calibration of the RF signals. Additionally, the picture shows also the beam shape and location in order to compare changes of RF signals (in particular forward and reflected) during the beam time.

DETUNING APPROXIMATION

The cavity detuning can be measured from derivative of the phase at the beginning of decay process. In fact, on the absence of driving voltage and beam the cavity field is oscillating with the resonant frequency of the cavity. The phase change relative to the reference RF signal gives exactly the detuning. The detuning over the whole pulse (only RF, no beam) one can calculate using equation (6).

$$\Delta\omega = \frac{d\angle V}{dt} - 2\omega_{12}\frac{|V_{for}|}{|V|}\sin(\angle V_{for} - \angle V) \tag{6}$$

where: $\angle V$ - cavity voltage phase; $\angle V_{for}$ - generator induced voltage phase; $\angle V_b$ - beam induced voltage phase

Certainly, the beam contribution can be added to equation (6) [2] but it is useless since we do not have the beam calibration. But the equation (6) can be used to calculate detuning for time periods when the beam is not present. This is actually a lot since usually, the beam covers only part of the flattop and at all other places detuning can be calculated. While detuning depends on mechanical behavior of the cavity and cannot change rapidly, it is possible to approximate detuning waveform during beam time and put it in equation (1). Approximation of the detuning was done with 2nd order polynomial for 3 operation regions: filling, flattop, and decay. At the borders, the approximation polynomials must evidently connect. Application of higher order polynomials seems to be not justified (Fig. 2).

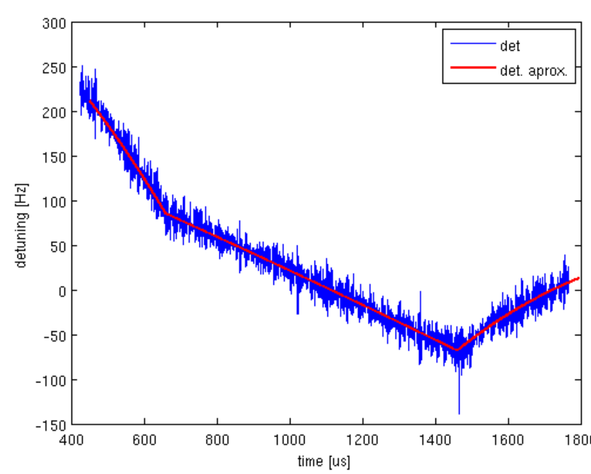

Figure 2: Detuning and its approximation for RF and beam signals from figure 1. The beam contribution is calibrated and taken into account.

MEASUREMENTS RESULTS

The proposed calibration method was tested at FLASH [3] accelerator during normal operation. All the signals were recorded using new MTCA based LLRF system [4]. It is equipped with 16 b resolution ADCs working at 81 MHz sampling rate. The measurements were performed at module ACC1 in the injector for 2 different beam patterns. The first one consists 200 bunches (0.4 nC) with 1 MHz repetition rate at FLASH1 and single bunch 0.3 nC at FLASH2 (see figure 1). The second one consist of 11 bunches (0.38 nC) with 1 MHz repetition rate at FLASH1 and 8 bunches 0.3 nC with repetition rate 100 kHz at FLASH2. For both beams, the same procedure was performed leading finally to obtain relative beam calibration of ACC1. The calibrations were averaged over 100 pulses, i.e. 100 pulses were recorded and then each of it was processed. The calibration results from all pulses were averaged. The precision of amplitude and phase calculation after averaging of 100 pulses were of order of 0.3% and 0.2 deg. respectively (standard deviation of the mean). Comparing result to reference (current calibration data at the machine) one have to remember it is only relative calibration, therefore only relative differences between cavities matters. Obtained results were recalculated to be comparable with current calibration used at the machine. Results are collected at Table 1.

For both beam patterns, good agreement was achieved. Results also fit nicely to the currently used calibration data. The phase error is of the order of 1 deg. which is comparable to the error of standard calibration measurements. The amplitude error is as high as ~10% for cavity 5 but typically is much lower. One has to mention that reference calibration was measured with beam consisting 30 bunches with bunch charge of the order of 1 nC. That may explain bigger discrepancies between results. What seems to be very important is consistent results with 2 very different beam patterns and intensity.

Some general impression about beam intensity effect on the estimated calibration data may be gained looking at figure 3. This is result of processing of old data, collected during "9mA" experiment [5] performed at FLASH. This data were recorded with much lower quality both in sampling rate and ADC resolution but these data are still valuable since the beam intensity was extremely high during this experiment. In the presented case the beam was changed from 60 up to 2400 bunches of 1.5 nC, i.e 40 times. In spite of this huge beam change the calibration looks pretty stable (around 10% at the amplitude and 2 deg. at the phase (fig. 3).

Table 1: Beam Calibration at ACC1@FLASH

Cav.	Beam 1		Beam 2		Reference	
No.	A	Phase	A	Phase	A	Phase
1	0.77	109.45	0.77	109.45	0.77	109.45
2	0.81	112.35	0.80	110.64	0.83	111.46
3	0.79	-152.98	0.79	-153.77	0.82	-153.64
4	0.84	41.34	0.82	40.60	0.77	41.54
5	0.87	-77.99	0.88	-77.82	0.76	-78.79
6	0.79	-16.06	0.80	-16.49	0.78	-16.95
7	0.75	-31.95	0.78	-31.58	0.75	-32.10
8	0.75	41.01	0.75	40.11	0.74	40.09

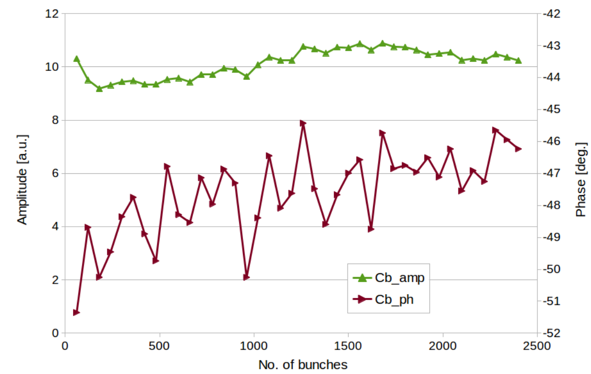

Figure 3: Dependency of calibration factors on beam intensity. Measurements were done at cav.1 ACC6 during "9mA" experiments. Beam current 4.5 mA, number of bunches variable in the range from 60 up to 2400 (3 MHz, 1,5 nC).

CONCLUSION

In the paper, the new method of the beam to RF field interaction estimation is discussed. Results can be used to calibrate sensors of the vector sum LLRF control. Since the method can be used during normal machine operation it may help to track changes and drifts in the control system. The results are consistent for various beam conditions, however, weak dependence on the beam intensity is expected. The method should be further tested and its limitations investigated. It was not observed so far but it is obvious that for low beams it will lose accuracy. One of possible disadvantage is complex and long computation time caused by fitting differential equations with a huge number of discretization points. Since the algorithm is currently implemented as Matlab script the computation lasts relatively long (ten pulses for one cavity takes about 15 minutes on 3 GHz CPU). If the method and algorithm confirms usefulness it should be implemented as a real server, possibly on multicore CPU. Since the computations for individual cavities can be easily parallelized it is possible to use GPU support.

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ISBN 978-3-95450-182-3