TRANSIENT BEAM LOADING BASED CALIBRATION OF THE VECTOR-SUM FOR THE TESLA TEST FACILITY

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1 ABSTRACT

In the TESLA Test Facility each klystron drives multiple cavities. The rf feedback system will regulate the vector sum of 16 cavities. Phase and amplitude errors of the individual cavity field probe signals result in a contribution to the energy spread in presence of microphonic noise. An energy spread contribution of $2.7 \cdot 10^{-4}$ for 16 cavities requires gradient calibration of ±10% and phase calibration of ±1˚ for a microphonic noise level of ±10˚. A procedure which meets these requirements is based on beam induced transients. For the phase offset calibration, the transients are observed at zero crossing and the offset is determined by nulling of the average transient by changing the cavity phase. The field calibration is accomplished by observation of the transients on crest when the beam current is known or relative calibration to other cavities if the beam current is not known. A description of the hardware, software, and calibration procedures are given, and results of measurements under actual operating conditions but with simulated beam are presented.

2 INTRODUCTION

The goal of the rf system is usually stated as maintaining the phase and amplitude of the rf signal within a given tolerance. Fast control is achieved by amplitude and phase modulation of the incident wave. If multiple cavities are driven by one klystron, it is not possible to maintain field control in the individual cavities. It is therefore necessary to control the vector-sum of the individual cavity voltages

$$V_{\mathrm{beam}} \cdot \cos(\varphi_{\mathrm{beam}}) = \sum_{i=1}^{N} V_i \cdot \cos(\varphi_i) \qquad (1)$$

The vector-sum is a direct measure of the energy gain of electrons arriving at the cavity at phase φ_{beam}. The vector-sum can be generated as the analog sum of the N cavity probe signals (at rf frequency or after conversion to IF or to baseband), or by numerical calculation of the vector sum from the digitized gradient signals. 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.

$$V_{\mathrm{meas}} \cdot \cos(\varphi_{\mathrm{meas}}) = \sum_{i=1}^{N} V_i \cdot \left(1 + \frac{\Delta V_i}{V_i}\right) \cdot \cos(\varphi_i + \Delta\varphi_i) \qquad (2)$$

In the presence of uncorrelated microphonic noise in the N cavities and perfect control of the measured vector-sum, the energy gain of the beam will fluctuate as a result of the finite and randomly distributed calibration errors.

3 REQUIREMENTS FOR RF CONTROL

The requirements for amplitude and phase stability are derived from the desired energy spread of the electron beam. Energy spread is induced by amplitude and phase fluctuations of the accelerating field and the finite bunch length.

3.1 Amplitude and Phase Stability

The energy spread requirements for the TTF Linac of $\sigma_E / E \le 2 \cdot 10^{-3}$ are fairly moderate. The requirements for correlated amplitude and phase stability are therefore on the order of 0.5% and 0.5°, respectively. For uncorrelated errors, the requirements for the regulation of the vector sum are relaxed by a factor of $\sqrt{K}$, where K is the number of klystrons. For the TTF with a total of 32 cavities two klystrons are used to drive 16 cavities each.

3.2 Calibration Accuracy for Vector-Sum

The calibration requirements for the vector-sum are dictated by the maximum allowable rms fluctuations of the accelerating voltage $V_{\mathrm{beam}} \cdot \cos(\varphi_{\mathrm{beam}})$. Assuming that the measured vector-sum is absolutely stable, the energy spread induced by the actual vector-sum is a function of the level of microphonics $\Delta\phi_{\mathrm{mic}}$, the gradient calibration error $\Delta V / V$, and the phase calibration error $\Delta\varphi$ in each cavity.

Assuming uniform distributions for these parameters, the contribution of calibration errors to the energy spread can be calculated. The dependency of the energy spread on phase calibration errors is shown in figure 1. A microphonic noise level of ±10˚ and a gradient calibration error of ±10% is assumed.

In the TESLA linac, the bunch-to-bunch energy spread contribution from 16 cavities may not exceed $2.7 \cdot 10^{-4}$ [1] demanding for an accuracy for the gradient calibra-

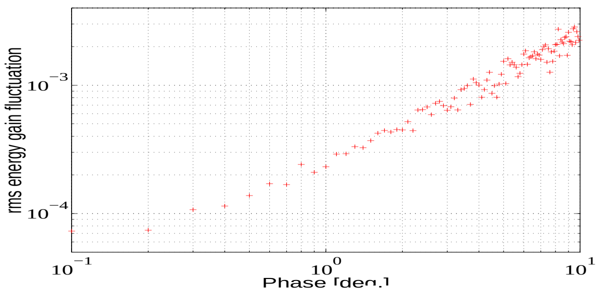

Figure 1: Energy gain fluctuations as function of phase calibration error.

tion of ±10% and of ±1° for the phase calibration. Phase calibration to this high degree of accuracy is a challenging task. Fortunately, it is possible to use the beam induced transients for the calibration.

4 CALIBRATION OF VECTOR-SUM

The calibration of the vector-sum can be done independently for gradient and phase. It should be noted that the calibration of the cavities relative to each other is of importance. Both, gradient and phase can - at least in principle - be determined from rf measurements.

Knowledge of Q_{ext} of the probe coupler, the cable attenuation, and the sensitivity of the gradient detector is sufficient for gradient calibration. The dominant error is with ±10% the calibration of the external Q of the probe coupler. Although this accuracy may be sufficient, it is desirable to perform an *in situ* calibration of the gradient.

The phase can also be determined by measurement of the electrical length of the field probe cables and the phase of the LO-reference at the down converter: The accuracy of this method is at best a few degrees but is more likely around 10 degrees. The phase calibration in the installed system is definitively desirable since more factors contribute to the overall error.

4.1 Principle of Phase Calibration

The goal is to adjust the cavity phase such that the beam passes the cavity at the zero crossing of the accelerating field as shown in figure 2.

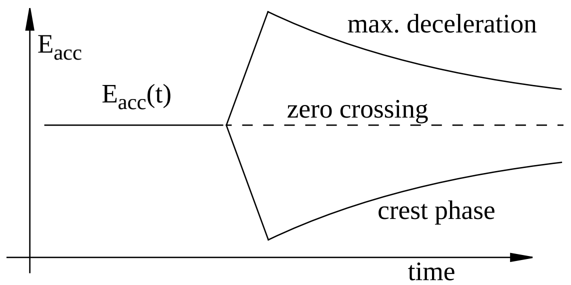

Figure 2 : Beam induced transient on crest, for maximum deceleration, and at zero crossing.

This is accomplished by variation of the cavity phase setpoint until the average (microphonics !) transients are nulled. The cavity phase is now at -90 deg. or +90 deg. The sign can be determined from a change in transient when increasing the phase setpoint. The phase is calibrated by adding a phase offset such that the measured phase reading is correct at zero crossing. Each cavity must be calibrated indivually.

4.2 Detailed Phase Calibration Procedure

The phase calibration must be performed while the vectorsum is regulated. This ensures that the energy gain of the 16 cavities is sufficiently stable (close to zero) from pulse to pulse and that the beam can be transported to the beam dump.

The phase calibration procedure must account for the presence of microphonic noise. The amplitude and phase fluctuations in the individual cavities are to be taken into account. Also the possibility of beam current fluctuations is to be considered.

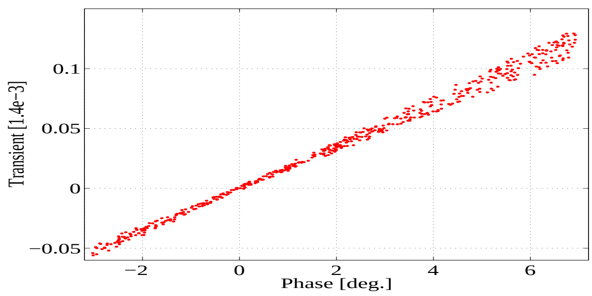

Figure 3: Beam induced transient as function of the measured cavity phase (simulation). The phase variations are a result of microphonics and can also be controlled with the phase set point. Current fluctuations are 10% and the phase detector noise corresponds to 0.1°.

A single data point would be sufficient if the magnitude of the transient as a function of measured phase, beam current, duration of transient, and cavity shunt impedance are known. With more data points, is is possible to derive beam current, and beam current fluctuations from the data. The detector noise is also determined from the measurement.

For small changes in measured phase and proximity to zero crossing, the beam induced transients are proportional to cavity phase and beam current. A least square fit is used to determine the phase offset for each cavity accurately.

5 TRANSIENT DETECTION BOARD

The input signal for the signal conditioner for the transients is the gradient signal. This signal is the output of a Schottky diode with a typical signal level of 5V at a gradient of 25 MV/m. The signal conditioner must subtract an offset which is determined by the gradient detector voltage just (a few µs) before the beam pulse arrives. The resultant signal is amplified by a gain of up to 100.

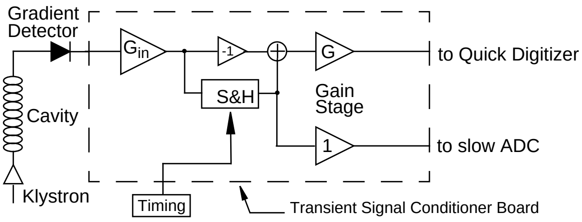

Figure 4 : Schematic of the transient detection board.

5.1 *Signal Level Consideration*

The transient amplitude for a 10 µs beam pulse at an average beam current of 8 mA is given by

$$\frac{\Delta E_{acc}}{E_{acc}} = \frac{t_{beam}}{\tau_{cav}} = \frac{10\mu s}{700\mu s} = 1.4 \cdot 10^{-2}, \quad (3)$$

since the steady state beam induced voltage is 25 MV/m, and the beam induced field changes linear with time if the pulse length is significantly shorter than the time constant of the cavity. The transient on the gradient signal also depends on the phase of the accelerating field ϕ_{beam} according to:

$$\frac{\Delta E_{acc}}{E_{acc}} = \frac{\Delta V}{V} \cdot \cos(\phi_{beam}). \quad (4)$$

A calibration accuracy of $\pm 1°$ requires resolving transients of $1.4 \cdot 10^{-2} \cdot \cos(89°) = 2.4 \cdot 10^{-4}$. Compared to the bit resolution of the 12 bit ADC of $2.4 \cdot 10^{-4}$, a signal level of 5V from the gradient detector at 25 MV/m, and a full range of the ADC of $\pm 5V$, a signal gain of 10 appears to be sufficient. The higher limit of the gain is set by the natural gradient fluctuation from microphonics and Lorentz force.

5.2 *Signal/Noise Measurements*

The transient signal conditioner boards have been tested with transients generated by the digital feedback system. The result of a measurement shown in Figure 5 indicates that a resolution of 1 degree in phase is possible.

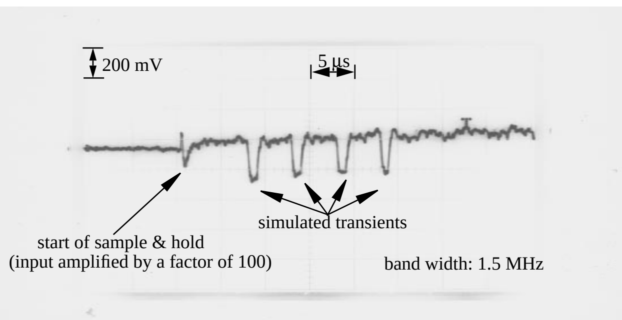

Figure 5 : Transients measured with dedicated transient signal conditioner board. Transients corresponding to 1° in phase can be resolved.

6 ACCURACY OF CALIBRATION

The overall performance of the transient detection has not yet been tested with a cavity. However, simulations have been performed to verify the feasibility of the proposed method.

The simulation models a superconducting cavity pulsed at 25 MV/m, microphonics modulating the phase at the time of beam injection, beam pulses including current fluctuations, and measurement noise. The amplitude of the measured transient as function of beam phase is shown in Figure 3. The simulation assumes beam current fluctuations $\pm 10\%$ and a measurement noise of $\pm 0.1°$. The measurement error is small since it is possible to use several hundred data points before and after the time of the beam transient to determine the cavity phase.

7 CONCLUSION

The calibration requirements for the vector sum of $\pm 1°$ presents a challenge to the rf system design. Fortunately the heavy beam loading of 8 mA allows for precise measurement of the beam induced transients. This method allows one to calibrate the vector-sum to the required accuracy. The same procedure will be used for precision phasing of the cavities, and the calibration of the gradient. Gradient calibration relative to other cavities can be achieved with high accuracy. Absolute calibration requires information on the beam current and the loaded Q of the cavity.

8 REFERENCES

[1] A. Mosnier, J.M. Tessier, CE Saclay, *Energy Spread Sources in TESLA and TTF*, TESLA Report 95-5