EXPERIENCE WITH THE CONTROL OF THE VECTOR SUM AT THE TESLA TEST FACILITY

A. Gamp, S. Goloborodko, A. Kholodnyi, M. Liepe, T. Plawski, K. Rehlich, T. Schilcher, S.N. Simrock, Y. Tchernoousko, DESY, M. Hüning, RWTH Aachen

1 ABSTRACT

In the rf system for the TESLA Test Facility each klystron will supply rf power to up to 32 cavities. The superconducting cavities are operated in pulsed mode and at high accelerating gradients. The control of significant Lorentz force detuning and precise calibration and measurement of the vector sum are the main issues to be solved. Presently installed are 8 cavities in the first cryomodule of the linac which have been in operation since June 97. Initial commissioning has been conducted in a very short time due to the extensive diagnostics available in the digital the rf control system. The paper describes commissioning of the rf system with emphasis on the calibration of the vector-sum, adaptive feedforward, and the various diagnostic tools available. RF control performance and plans for the control of 24 cavities are also presented.

2 INTRODUCTION

The rf system at the Tesla Test Facility [1] must maintain the accelerating field within given tolerances [2] during beam acceleration. The pulsed cavity field - defined as the vector sum of up to 32 cavities - consists of three segments (see fig. 1):

- cavity filling time (500 μs)
- beam-on (flat-top) time (800 μs)
- cavity field decay ($\tau_c = 700\ \mu s$).

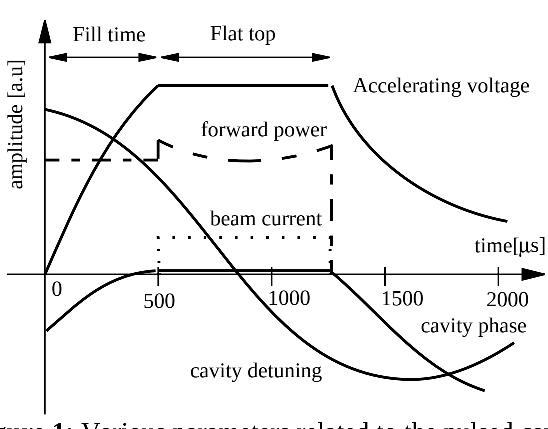

Figure 1: Various parameters related to the pulsed cavity fields in the superconducting cavities of the TESLA Test Facility.

The control of the cavity field has been considered a challenging task for the following reasons:

- the Lorentz force will detune the cavity by more than one cavity bandwidth during a 1.3 ms rf pulse. Therefore additional power is needed for rf control,
- microphonics will modulate the pre-detuning of the cavity at the begin of the pulse and increase peak power requirements necessary for control,
- the vector-sum must be calibrated to better than ±10% for the gradient and ±1° in phase for each cavity to achieve an rms energy gain stability of 2.7×10^{-4} assuming a microphonic noise level of ±10°,
- the vector-sum of 32 cavity probe signals must be regulated to an amplitude stability of the order of $\sigma_A/A \le 2\cdot10^{-3}$, and a phase stability of $\sigma_\phi \le 0.5°$,
- beam loading transients of $\Delta A/A = 1.4\cdot10^{-3}$ with TTF Injector II: the bunch charge is $5\cdot10^{10}\ e^-$, and the repetition rate is 1 MHz which corresponds to an average beam current during the beam pulse of 8 mA.

The feedback system for the TTF has been designed as a fully digital system [1] to provide a time varying cavity field setpoint which is important during the cavity filling. A time varying feedforward [3] is applied to compensate repetitive perturbation such as the dynamic Lorentz force detuning and beam loading. Extensive build- in diagnostics allow for precise calibration of the vector sum [4] and inform the operator about beam phase, cavity detuning, loaded Q of the cavity, and the feedback loop phase [5].

3 OPERATOR INTERFACE

The digital rf feedback system employs tables for real and imaginary components of the cavity field setpoint, feedback gain, and feedforward signal to allow for time varying vectors for these parameters. To simplify the generation of the setpoint tables the operator only need to provide input for the following parameters:

- cavity gradient and cavity phase
- start time for cavity filling, cavity fill time and flat top duration

The feedforward tables are derived from the cavity setpoints but additional information about phase offset between setpoint phase and feedforward table, power reduction ratio after cavity filling, and beam parameters such as beam current, phase, duration, and injection time are needed. Hardware signal scaling factors require a one time adjustment during commissioning.

4 CALIBRATION OF THE VECTOR SUM

Since 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. The calibration of the vector-sum is based on beam induced transients [4] and is implemented as open loop and closed loop version. The open loop implementation achieves higher resolution since it uses the 14-bit ADCs in the digital feedback while the closed loop version maintains constant acceleration but suffers from the lower resolution 12 bit ADCs used for the measurement of the incident wave.

The accuracy of the calibration depends solely on the accuracy with which the beam current is known (about 1%), the cavity shunt impedance (r/Q)*Q_L and the magnitude of the transient which depends on the beam duration. With 30 µs beam pulses at an average current of 8 mA, a loaded Q of $2*10^6$, and (r/Q)=1030 Ω the induced transients are of the order of 1 MV/m which can measured with an accuracy of better than 1%.

The calibration of the vector-sum requires only 10 minutes of dedicated open loop operation. A typical calibration accuracy of 5% for gradient and 3 degrees for phase has been achieved mainly limited by the accuracy of the beam current calibration. The calibration of the vector sum has been verified with the spectrometer. Relative calibration accuracy is expected to be better than 2% and 1 deg. respectively. In the future the calibration process will be fully automated and used to track any changes in calibration.

5 RF SYSTEM OPERATION

The startup procedure has been simplified greatly by use of automated procedures. The following steps are usually necessary to run the rf system:

- Load vector-sum calibration parameters.
- Open loop operation without beam. Adjust feedforward scaling parameters to approximate operating gradient.
- Determine loop phase.
- Closed loop operation without feedforward and beam. Adjust closed loop parameters to match open behavior approximately.
- Add feedforward.
- Turn beam on.
- Determine beam phase and adjust to operation on crest
- Activate beam loading compensation and adjust necessary parameters.
- Verify loaded Q and phases of incident waves. Adjust phase of incident wave with wave guide tuner.
- Activate adaptive feedforward.

With the new operator interface described a trained operator can turn the rf system on within 10 minutes. It is planned to automate the above described procedure in the future. Presently all exception handling as a result of interlock trips such as cavity quench, coupler window arc detector and many others must be reset by the operator. During a typical run some interlock trips occur during the turn on phase while the trip rate during routine operation is very low (less than 1 trip of any type per hour).

6 RF SYSTEM DIAGNOSTICS

Several rf utilities assist the rf system user during accelerator operation.

6.1 Loop Phase

The loop can be determined easily during open loop operation. If the phase of the incident wave is held constant during the first few ten microseconds of cavity filling, the loop phase can be determined by measurement of the phase angle of the cavity field during times short compared to the time constant of the cavity. This method allows for a detuning independent measurement of the loop phase. The accuracy of the measured loop phase in a single pulse is about 1 degree but can be improved by averaging over several pulses.

6.2 Beam Phase

The beam phase is calculated by the method of system identification [5] which gives a best estimate of the parameters in the rf system model. The time varying beam phase of individual cavities or the vector-sum can be determined in open or closed loop configuration with an accuracy of a few degrees during a single macropulse. A better accuracy can be achieved by averaging if the signals are repetitive.

6.3 Loaded Q and Cavity Detuning

The loaded cavity Q and the cavity detuning at the end of the rf pulse can be determined from the slope of cavity gradient and cavity phase respectively. Using the first two hundred microseconds of the field decay one yield a single pulse accuracy of 1% for loaded Q and 0.5 Hz for the cavity detuning. Measurement of cavity detunings for several pulses allows to display the probability density of the resonance frequency which is a measure for the amplitude of the microphonic noise.

6.4 Lorentz Force Detuning

A very interesting application of system identification is the measurement of the time varying detuning during the rf pulse. The method an the result are described in detail in [5]. A typical result is shown in figure 2. It can be seen that the lorentz force detuning is about ±10Hz at 15 MV/m.

6.4 Phase of Incident Wave

Also the phase of the incident waves is determined by the system identification tool. The phase can be determined with an accuracy of 3 degrees and can be used to adjust the three stub wave guide tuner which have a typical tuning range of ±100 degrees.

7 ADAPTIVE FEEDFORWARD

In addition to the feedback control loop which suppresses stochastic errors, feedforward is applied to reduce repetitive perturbations induced by beam loading and dynamic lorentz force detuning. The error reduction with the feedforward is significant since repetitive errors are dominant. The feedforward algorithm first identifies the time varying state space model of the closed loop system by measurement of a step response. Next the pulse to pulse average of the measured perturbations is applied to the inverse state space model to obtain the correct feedforward table. The feedforward tables can be updated continuously to follow slow changes in the perturbation parameters. On-line system identification is transparent to routine beam operation due to the small step size used.

8 RF CONTROL PERFORMANCE

The requirements of $\sigma_A / A \le 2 \cdot 10^{-3}$ for amplitude stability and of $\sigma_\phi \le 0.5°$ phase stability can be achieved with a feedback gain of 70 while the feedforward is turned off. The residual fluctuations are dominated by a repetitive component which can be further reduced by a factor of 10 with the adaptive feedforward thereby exceeding the design goals significantly. The high degree of field stability is mainly due to the low microphonic noise levels. A typical result of measured field stability without and with the adaptive feedforward is shown in Figure 3

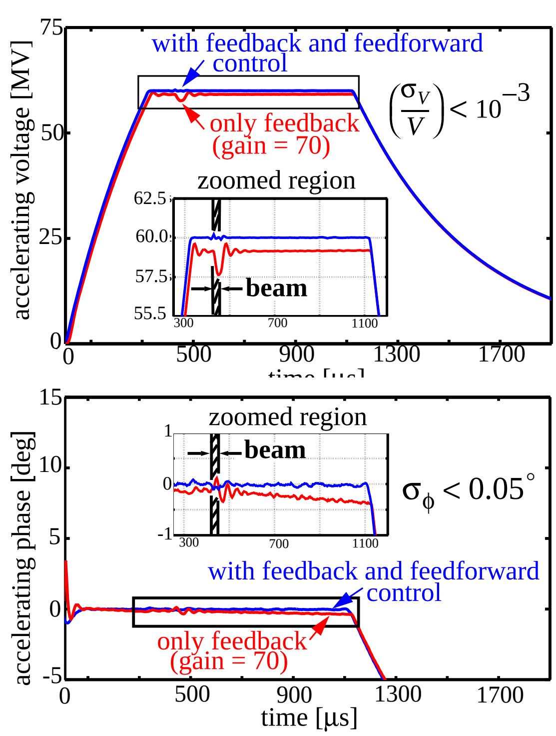

Figure 3: RF control system performance without and with adaptive feedforward.

9 CONTROL FOR 24 CAVITIES

It is planned to extend the rf feedback system for the control of the vector sum of the 24 cavities in the first three cryomodules by end of this year. The feedback algorithm will be improved and include Smith predictor and Kalman filter to allow for an increase in loop gain and simultaneous reduction of electronic noise in the loop. It is also desirable to operate individual cavities at their maximum operable gradients. This can be achieved with certain restrictions by appropriate adjustment of the loaded quality factor using the three stub wave guide tuner.

10 CONCLUSION

The digital rf control system exceeds the requirements for field stability significantly mainly due to the small microphonics levels. It will still meet the requirements up to microphonic levels of ±50 Hz.Rf operation is greatly simplified by an operator interface which calculates the tables needed for setpoint and feedforward including beam compensation from a few essential parameters. Extensive diagnostics for loop phase, beam phase, cavity detuning and other parameters allow the operator to turn the system on within 10 minutes. The critical issues such as calibration of the vector-sum, control of lorentz force detuning, microphonics and beam loading have been solved by appropriate design of the rf system.

11 ACKNOWLEDGEMENTS

We gratefully acknowledge the support from the linac operations group. Their dedicated support in all linac commissioning issues has been the basis for our success.

12 REFERENCES

[1] S.N. Simrock, I. Altmann, K. Rehlich, T. Schilcher, *Design of the Digital RF Control System for the TESLA Test Facility*, EPAC 96, Sitges (Barcelona), Spain, June 10-14, 1996, p. 349

[2] S.N. Simrock, I. Altmann, K. Rehlich, T. Schilcher, *Operational Aspects of the RF System for the Test Facility*, EPAC 96, Sitges (Barcelona), Spain, June 10-14, 1996, p. 1869

[3] M. Liepe, S.N. Simrock, *Adaptive Feed Forward for Digital RF Control System for the TESLA Test Facility*, these proceedings

[4] S.N. Simrock, T. Schilcher, *Transient Beam Loading based Calibration of the Vector-Sum for the TESLA Test Facility*, these proceedings.

[5] M. Hüning, S.N. Simrock, *System Identification for the digital RF Control for the TESLA Test Facility*, these proceedings