REQUIREMENTS FOR RF CONTROL OF TTF II FEL USER FACILITY

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Abstract

During the past years, the experience gained with the operation of RF system at the TESLA Test Facility (TTF)[1] resulted in several modifications and improvements of its design. In addition, as the TTF is converted to become a user facility TTF II for the SASE-FEL during 2004. The electron beam energy will be increased from 250 MeV/c up to 1 GeV/c by installation of 6 TESLA cryo-modules. The RF system include 4 klystrons, each of them will supply RF power to group of cavities (rf gun, module 1, module 2&3, module 4,5&6). This paper presents the performance of the digital RF control at TTF I, commissioning/extension and features of the RF control for the upgrade of the TTF II.

1 INTRODUCTION

At TTF I significant progress has been made on the issues of pulsed operation of superconducting cavities at high gradients with respect to Lorentz force detuning and the associated resonant excitation of mechanical resonances, microphonics, the transients induced by the pulsed beam, and the control of the vector-sum of multiple cavities driven by single klystron.

Considerable experience of RF control at high gradients close to 20MV/m with pulsed RF and pulsed beam has been gained at the TTF. The RF control system employs a completely digital feedback system[2] to provide flexibility in the control algorithms, precise calibration of the vector-sum, and extensive diagnostics and exception handling capabilities. Presently under study is a piezotranslator based active compensation scheme for the time varying Lorentz force detuning which if successful will reduce RF power requirements at gradients >25MV/m considerably and provide improved field stability[3].

The requirements for amplitude and phase stability of the vector-sum a group of cavities are driven by the maximum tolerable energy spread for the TESLA Test Facility. The goal is an rms energy spread of $\sigma_E/E = 10^{-3}$. The requirements for gradient and phase stability are therefore of the order of 10^{-3} and $0.3°$ respectively.

The amplitude and phase errors to be controlled are of the order of 5% for the amplitude and $20°$ for the phase as a result of Lorentz force detuning and microphonics. These errors must be suppressed by a factor of at least 40 which implies that the loop gain must be adequate to meet this goal. Fortunately, the dominant source of errors is repetitive (Lorentz force and beam loading) and can be reduced by use of feedforward significantly.

2 RF CONTROL PERFORMANCE FOR THE TTF I

Fast amplitude and phase control is accomplished by modulation of the RF signal to the klystron which will drive group of cavities. Digital I/Q detectors are used for the cavity field, and incident and reflected waves. The RF signals are converted to an intermediate frequency of 250kHz and sampled at a rate of 1MHz (i.e.two consecutive measurements describe I and Q of the cavity field). The cavity field vector defined by I and Q is multiplied by 2x2 rotation matrices to correct for phase offsets and to calibrate the gradients of the individual cavity probe signals. The vector-sum is calculated and corrected for systematic measurements errors. Finally the setpoint is subtracted and the compensator filter is applied to calculate the new actuator setting (I and Q control inputs to the vector-modulator). Feedforward is added from a table in order to minimize the control effort. The feedforward tables are adaptively updated to reflect slow changing parameters such as average cavity detuning, changes in klystron gain, phase shift in the feedforward path, and general changes in operating parameters. The RF control system has been completely integrated into the TTF control system DOOCS[4]. The operation is automated by the implementation of a DOOCS finite state machine server[5], which has access to high level applications. The start up, restart and routine operation of cryo-modules are automated. The state machine process includes loop phase measurement and correction, feedforward and feedback parameter adjustment, beam loading compensation, calibrations, and automatic fault recovery.

The cavities at TTF I have been routinely operated at a gradient of 15MV/m providing a beam energy of 250 MeV/c. The requirements of for amplitude and phase stability have been achieved with feedback only, the stability being verified by beam measurements. The residual fluctuations are dominated by a repetitive component which is further reduced by the adaptive feed forward by about one order of magnitude, thereby exceeding the design goals significantly.

Despite the fact that second bunch compressor is installed between the two cryo-modules all 16 cavities driven by a single klystron. In TTF mode the bunch compressor was by-passed by a straight section and the vector-sum of 16 cavities was controlled. During FEL operation only the vector-sum of the first 8 cavities was regulated in order to maintain stable injection conditions into the bunch compressor. The cryo-modules also were operated in different gradients by changing power balance between the modules. During the last run each cryo-module was driven by separate klystrons and each cryo-module was controlled by its own feedback loop. Cryo-module 1 at location ACC2 (Module 1*) has been tested at high gradient (close to 25MV/m) with closed feedback loop.

During the initial start-up time the individual cavity gradients and phases relative to the beam are calibrated using beam induced transients. The phases of the incident waves are adjusted to be equal in all cavities by means of motorized tree stub waveguide tuners. The calibration is verified by a measurement of the beam energy. The gradient calibration error was in the range of 3-5%. The measurement of beam induced transients (vectors) is shown in Figure 1 as the difference of the cavity field with and without transient during the beam pulse.

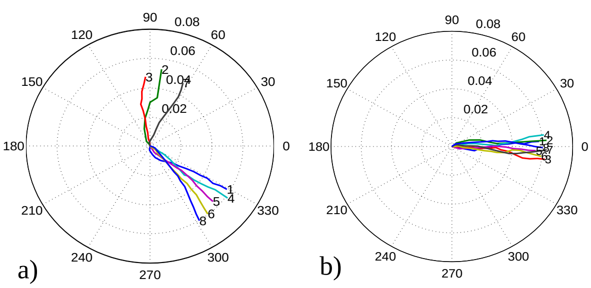

Figure 1: Measurement of beam induced transients at Module1* a) before and b) after adjustment of cavities phases.

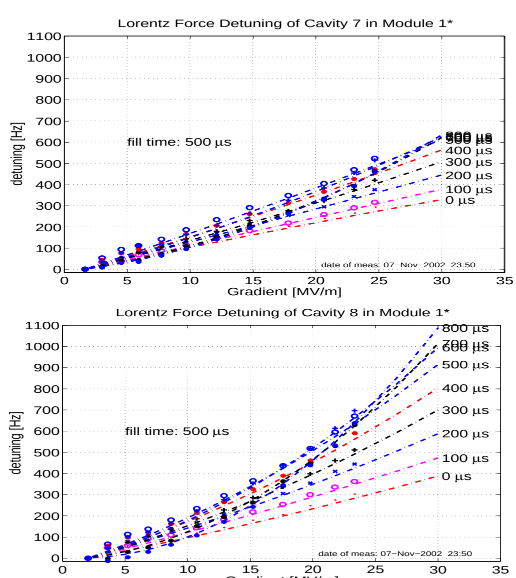

Figure 2: Lorentz force detuning measurement at Module 1* at high gradient for different flat-top duration.

In Figure 2 the data shows the cavity detuning as a function of gradient for different times during the flat-top. While the symbols reflect the actual measurement data, the curves are extrapolated to 30 MV/m using a second order polynomial. The Lorentz force parameter is different for different cavities. The high degree of field stability is mainly due to the low microphonic noise levels. The microphonic noise levels of the cavities are less then 10Hz rms.

3 RF CONTROL REQUIREMENTS

The requirements for the RF control system are usually defined in terms of phase and amplitude stability of the accelerating field during the flat-top portion of the RF pulse. In addition operational demands may impose further needs on the design of the RF control system.

3.1 Amplitude and Phase Stability

The requirements for the RF control system are derived from the desired beam parameters such as bunch-to-bunch and pulse-to-pulse energy spread. The beam parameters can be translated in to the requirements for phase and amplitude of the accelerating field of individual cavities or the vector-sum of several cavities driven by one klystron. TTF II requires tight field control of the order of 0.1% for the amplitude and 0.3° for the phase. Additional requirements are imposed on the accuracy of the calibration of the vector-sum which must be of the order of 10% for amplitude and 1% for phase in presence of +-10% microphonics.

More issues that need to be considered are:

- Control of the cavity resonance frequency. Here the critical issue is the precise measurement of the cavity detuning which can be derived from the relationship of incident and reflected wave or especially attractive in the pulsed case from the slope of the phase during decay of the cavity field following the RF pulse.
- Excitation of other passband modes by generator and beam. This is especially critical if harmonics of the beam coincide with other passband frequencies. Also field detectors may not detect the actual field seen by the beam.
- Operation close to klystron saturation will result in strong dependency of loop gain with klystron output power.
- The phase of the incident wave (and loaded Q) of each cavity must be controllable by means of remotely controlled wave guide tuners or phase shifters.
- Exception handling. In case of interlock trips or abnormal operating conditions (wrong loop phase or completely detuned cavity) the control system must ensure safe procedures to protect hardware and avoid unnecessary beam loss.

3.2 Operational Requirements

The RF control system must be operable, reliable, reproducible, well understood and meet technical performance goals. Besides field stabilization the RF control system must provide diagnostics for the calibration of gradient and beam phase, measurement of the loop phase, cavity detuning, and control of the cavity frequency tuners. Exception handling capability must be implemented to avoid unnecessary beam loss. Features such as automated fault recovery will help to maximize accelerator up-time. A thorough understanding of the RF system will allow for operation close to the performance envelope while maximizing accelerator availability. Often the RF control must be fully functional over a wide range of operating parameters such as gradients and beam current. For efficiency reasons the RF system should provide sufficient control close to klystron saturation.

The cavities are limited in their maximum operable gradients by quench, field emission or coupler sparks. Maximum operable gradient can be achieved with proper exception handling.

A cavity quench results in several effects:

- Field breakdown as shown in Figure 3 and resulting change in beam energy gain if the regulation of vector-sum cannot be maintained.
- Increase in cryogenic heatload.
- Increase in incident power to couplers and cavities if feedback gain is high and subsequent increased chance of coupler sparks and quench/field emission in other cavities due to increase of gradient. The beam energy may be constant if sufficient power is available. If cavities are operated in feed forward mode only, the energy gain of the beam will drop especially towards the end of the pulse.

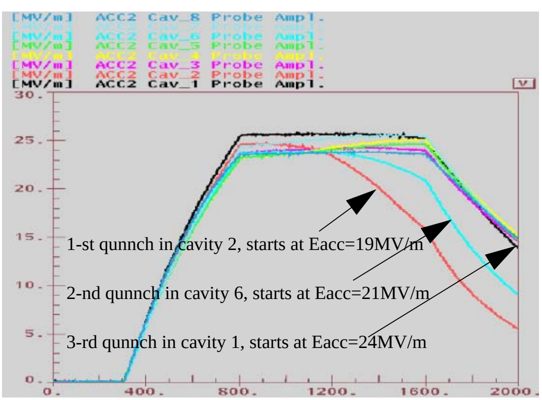

Figure 3: Quench detection during high gradient run at Module 1*.

Several measures can be taken to avoid cavity quench and to achieve desired stability:

- Turn-off klystron if cavity or coupler fault occurs.
- Reduce gradient in rf station where fault occurs.
- Reduce pulse length (rf and beam) if fault occurs.
- Detune cavity in which fault occurs.
- Change loaded Q of cavity in which fault occurs.

The mentioned task requires fast quench detection mechanism which can be implemented by including detuning and loaded Q measurement within DSPs.

3.3 Diagnostics

Diagnostics are required for calibration of gradient and phase with respect to beam, loop phase, incident wave and reflected wave, cavity detuning, loaded Q, etc.

- Loop Phase. The loop phase is determined during open loop operation by comparison of the vector controlling the actuator and the field vector induced in the cavity.
- Gradient and phase. Initial coarse calibration with RF, precise calibration with beam induced transients.
- Detuning and loaded Q. During decay of the cavity field the slope of gradient and phase (with respect to master oscillator) determine detuning and loaded Q.

4 CONCLUDING REMARKS

TTF I RF system was operational more then two years with a basic state machine for automated operation. Pulsed operation of superconducting cavities has been successfully demonstrated and has proven that the phase and amplitude stability requirements can be meet even in the case of control of the vector-sum of multiple cavities.

The future developments will be able to make use of advances in electronics. Faster DSPs reduce latency and allow more complex algorithms. Phase and gradient calibration based on beam induced transient can be improved to detect small transients with high precision thereby reducing beam loss in the accelerator when phasing the linac.

The future development plans includes: implement fast quench detection mechanism by including detuning and loaded Q measurement within DSPs; exception detection capability for individual cavities; extensive upgrade of finite state machine by implementation of automatic cavity/module tuning procedure and automated waveguide tuner control; develop robust and fast algorithm for adaptive feed forward; improve hardware diagnostic system by integrating diagnostic system within operational programs.

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