RF CONTROL SYSTEM FOR THE DESY VUV-FEL LINAC

Valeri Ayvazyan, Gevorg Petrosyan, Kay Rehlich, Stefan N. Simrock, Petr Vetrov
DESY, Hamburg, Germany

Abstract

In the RF system for the Vacuum Ultraviolet Free Electron Laser (VUV-FEL) Linac each klystron supplies RF power to up to 32 cavities. The superconducting cavities are operated in pulsed mode and high accelerating gradients close to the performance limit. The RF control of the cavity fields to the level of 10^{-4} for amplitude and 0.1 degree for phase however presents a significant technical challenge due to the narrow bandwidth of the cavities which results in high sensitivity to perturbations of the resonance frequency by mechanical vibrations (microphonics) and Lorentz force detuning. A digital RF control system has been developed for the VUV-FEL which will demonstrate the required control performance. Presently the Linac is being commissioned, and this effort provides the first full integrated test in the accelerator, including cryogenics, RF, beam transport, and beam diagnostics. The RF control system design and objectives are discussed.

INTRODUCTION

VUV-FEL Linac is the second stage of the TESLA Test Facility[1]. It is designed to accelerate electrons to an energy up to 1 GeV. The injector consists of a laser-driven photocathode in a 1.5-cell rf cavity operating at 1.3GHz with a peak accelerating field of 40MV/m on the cathode. The electron injector section is followed by a total of five 12.2m long accelerating modules each containing eight 9-cell superconducting niobium cavities. With the accelerated electrons a free electron laser will produce coherent, monochromatic light. The wavelength of the light depends on the energy of the accelerated electrons. It can be tuned between 6nm and 120nm.

First successful operation of the VUF-FEL at a wavelength of 32nm have been achieved. The accelerator provide the beam energy of 440MeV required for 32nm radiation wavelength. Since the accelerator is capable of achieving much higher beam energy such that, in a next step of the project, wavelengths around 10nm are planned.

Considerable experience of RF control at high gradients close to 20MV/m with pulsed RF and pulsed beam has been gained at the VUV-FEL. The RF control system employs a completely digital feedback system[2] to provide flexibility in the control algorithms, precise calibration of the accelerating field vector-sum, and extensive diagnostics and exception handling capabilities.

RF CONTROL REQUIREMENTS

The RF control requirements for amplitude and phase stability are usually derived from the desired beam parameters. It is also important to include operational issues such as turn on of the RF system, calibration of gradient and phase, and control of the waveguide and frequency tuners.

Amplitude and Phase Stability

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 VUV-FEL Linac. The goal is an rms energy spread of $\sigma_E/E = 10^{-4}$. The requirements for gradient and phase stability are therefore of the order of 10^{-4} and 0.1 degree 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 more then 100 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.

The requirements for the phase stability become also more severe for off-crest operation. In the case of the control of the vector-sum of several cavities driven by one klystron, the requirement for the phase calibration of the vector-sum components may become critical depending on the magnitude of microphonics.

Operational Requirements

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. 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.

RF CONTROL HARDWARE

Figure 1 shows the schematic of the RF control system at VUV-FEL. The hardware[3] of the digital feedback for 32 cavities consists of a DSP board with 8 Gigalink interfaces, four 8-channel ADC boards (14-bit, clocked at 1MHz) with Gigalink interface, and one 8-channel DAC board with Gigalink interface. A functional generator with VME interface drives a vector-modulator which produces the local oscillator (LO) signal generated from the

 0-7803-8859-3/05/$20.00

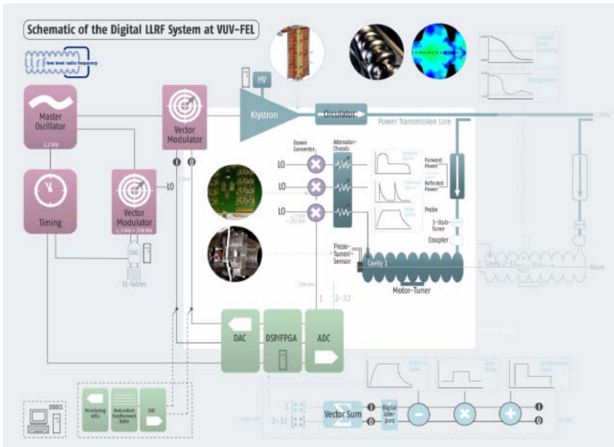

Figure 1: Schematic of the Digital RF Control System at

1.3GHz. It swiches the LO phase by 90 degrees every microsecond. Digital I/Q detectors are used for the cavity field, and the incident and reflected waves.

The digital boards are generic and flexible enough to be usable for a variety of control and data processing applications.

Multichannel DSP Module

The Multichannel DSP module (figure 2) is high performance floating-point digital signal processor (DSP) board in a VME standard (with eight 1.6Gbit per second serial links - Gigalink). It is designed for fast control applications requiring high performance and flexibility. Good system adaptability is provided by the usage up to 8 high speed serial links. The DSP can receive/transmit simultaneously up to eight data frames from/to different source/destination, make conversion and calculation. It is powered with Texas's floating point chip - TMS320C6701-167. The TMS320C6701 DSP uses the VelociTITM modified VLIW architecture, with up to eight instruction units operating in parallel. Full-speed internal program and data memories provide the bandwidth required for high data throughput. Data acquisition and memory block transfers are handled in background by a 4-channel DMA controller. The C6701 DSP's Host Port Interface (HPI) is usable as an expansion port, which provides an additional path for high-speed data acquisition from VME (up to 20 MB per second), enabling very high sample rates to be handled without any need for external buffers and FIFOs. Programming of DSP can be done via VME HPI or JTAG interfaces.

The Gigalink channels are grouped in two blocks by four channels sharing two controls FPGAs. Gigalink operation is controlled by logic implemented in FPGA. Third SPARTAN-II provided basic VME-bus decoding and interface between VME and HPI of DSP. Besides this, the chip includes controller for FLASH memory (1MB). This memory is used for fetching the code to be executed at system startup and can be used by applications for non-volatile data storage.

One of the reasons to use SBSRAM is quick load/storage of data from Gigalink during normal read operation by DSP. Then VME Master can read these data. The special controller of SBSRAM will convert DSP read operation to write SBSRAM operation when data is read out from Gigalink controllers.

The DSP also has one SDRAM pool - 16MB on the board. SDRAM is implemented for storage large amount of data and application software. This DSP module is a single-wide slave VME module (A16/D16). It should support 8 Gigalink connections (I/O interface to ADC, DAC or other DSP).

Figure 2: Multichannel DSP Module.

Gigalink Mezzanine Module

The Gigalink Meazzanine Module (figure 3) is a realized as small daughter board, which is used with special Carrier Board and provides interface between high speed serial data line and Carrier Board (ADC, DAC, Evaluation Board).

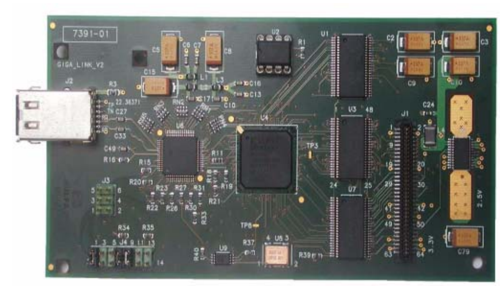

Figure 3: Gigalink Mezzanine Module.

RF CONTROL SOFTWARE

Control algorithm

The digital feedback controls in-phase and quadrature component of the cavity field. High frequency probe signals are used to measure the accelerating field in the individual cavities. These 1.3 GHz signals are converted to 250 kHz and sampled by the ADCs with 1 MHz rate, i.e.

two subsequent data points describe I and Q component of the cavity field. The samples are scaled and rotated to compensate the delay in the cable length and calibrate the fields in the individual cavities. Then the sum of individual field vectors is calculated and rotated to adjust the loop phase. The vector sum is filtered by the low pass filter and the feedback algorithm applies the proportional gain to the regulating error values (table). A feedforward table is added to the value of the calculated control action. The real and imaginary part of the calculated table are converted by the DACs separately and control the RF vector, applying the correction signal to the vector modulator.

The control algorithm has been implemented in DSP system. For fast calculation the program was written in assembler. It allows calculation control signal for 32 cavities in 1µs.

Server Programming

The RF control system has been completely integrated into the VUV-FEL control system DOOCS[4]. The DOOCS approach defines each hardware device as a separate object and this object is represented in a network by a device server, which handles all device functions. The RF control system is naturally integrated with the VUV-FEL control system, by development several DOOCS servers devoted to functionally self consistent part of it and the required client applications for the system management and diagnostic. The DSP server controls the DSP board hardware and contains the required functionality for managing the digital feedback subsystem. A client application can has access to the server data using DOOCS application programming interface (API). The operation at TTF was 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 were automated. The state machine process includes loop phase measurement and correction, feedforward and feedback parameter adjustment, beam loading compensation, calibrations, and automatic fault recovery.

Application Software

A set of generic and specially devoted programs provide the tools for the operators to control the RF system. Some of them are created based on the MATLAB, LabVIEW or ROOT, others are in-house developed DOOCS client applications. However all of them use the DOOCS API to access the data. The application software includes automated operation of the frequency tuners, calibration of the vector-sum, phasing of cavities, and adjustment of various control system parameters such as feedback gains, feed forward tables, and setpoint correction during cavity filling. Extensive diagnostics inform the operator about cavity quenches, cavities requiring manual tuning, and an excessive increase in control power.

PERFORMANCE RESULTS

Currently the cavities are operating at different gradients up to 20MV/m providing a beam energy of 440 MeV. The requirements of $\sigma_E/E = 10^{-4}$ for amplitude stability and 0.1 degree phase stability have been achieved with feedback only, the stability being verified by beam measurements[6]. 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. The high degree of field stability achieved is mainly due to the low microphonic noise levels.

CONCLUSION

A digital RF control system has been developed to control the vector-sum of the accelerating field of group of superconducting cavities powered by a single klystron. The RF control system is realized as a driven feedback system 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 goal to provide a constant accelerating field in order to minimize the energy spread has been successfully reached. The major advantages of the system are the built in diagnostics, flexibility and configurationally which are essential for the extension of up to 32 cavities driven by one klystron.

ACKNOWLEDGEMENTS

We gratefully acknowledge the contributions from for A. Matyushin, G.Moeller and V. Yakimchuk for their dedicated support. We also want to express our thanks to the VUV-FEL Operation Team for their valuable comments and helpful discussions.

REFERENCES

[1] “The Conceptual Design Report for the TESLA Test Facility”, Edited by D.A. Edwards, DESY, 1995

[2] S.N. Simrock, I. Altmann, K. Rehlich, T. Schilcher, “Design of the Digital RF Control System for the TESLA Test Facility”, Proc. EPAC’96, Barcelona, Spain, p.349, 1996

[3] V.Ayvazyan, G.Petrosyan, K. Rehlich, S.N.Simrock, P.Vetrov, “Hardware and Software Design for the DSP Based LLRF Control”, Proc. PCaPAC’05, Hayama, Japan, 2005

[4] G. Grygiel, O. Hensler, K. Rehlich, “DOOCS: a Distributed Object Oriented Control System on PC’s and Workstations”, ICALEPCS 97, Beijing, 1997

[5] V. Ayvazyan, K. Rehlich, S.N. Simrock, N. Sturm, “Finite State Machine Implementation to Automate RF Operation at the TESLA Test Facility”, Proc. PAC’01, Chicago, p.286, 2001

[6] V. Ayvazyan, H.Schlarb, “TTF Electronic Logbook Entry from 29.04.2005 15:52”, http://ttfinfo.desy.de/TTFelog/index.jsp

