

STATE OF THE ART IN RF CONTROL

S.N. Simrock, DESY

Abstract

Nowadays the designer of a new rf control system has access to a wealth of powerful digital, analog, and rf circuitry. The requirements for the rf control system have changed from only controlling the amplitude and phase of the accelerating field to the required degree to stability. Additional tasks include exception handling and extensive build-in diagnostics while pursuing issues related to reliability, operability, and maintainability. Also operation close to the performance limit must be supported while maximizing the availability of the accelerator. With many accelerator projects in planning or under construction several state-of-the art rf control designs have evolved. This paper will present an overview of this new technology and discuss its performance.

INTRODUCTION

The architecture of a typical RF control system is shown in Figure 2. A power amplifier provides the rf power necessary for establishing the accelerating fields in the cavities. The cavity field is measured and the compared to a setpoint. The resulting error signal is amplified and filtered and drives a controller for the incident wave to the cavity. A frequency and phase reference system provides the necessary rf signals. The requirements for the stability of the accelerating fields range from 1% in amplitude and 1 degree in phase for high power H⁻ accelerators to 0.01% in amplitude and 0.01 degree in phase for the critical sections such as compressors in XFELs. Since many of the present and near future accelerator based facilities are employing superconducting cavity technology this review will focus on rf control systems for sc-cavities. Accelerator projects making use of the present state of the art technology include SNS, J-PARC, CEBAF upgrade, RIA, the European X-FEL, the BESSY soft X-Ray Laser, the Cornell ERL, and many others. Descriptions of the design of the llrf system that have been developed recently for the various accelerator projects can be found in [1-21].

RF CONTROL SUBSYSTEMS

The subsystems shown in the architecture of the rf system in Figure 2 are shown in more detail in Figure 5. Most recent advances in technology have been achieved in the area of the digital controllers including high speed analog I/O and powerful signal processing, the area of field detection, frequency conversion and actuators for field control, fast piezoelectric and magnetostrictive cavity frequency

timers, low noise reference frequency oscillators and highly stable frequency distribution systems.

CAVITY FIELD DETECTION

The cavity field detection can be accomplished with traditional amplitude and phase detectors or with IQ detectors which operated directly at the rf operation frequency or at an intermediate IF frequency which contains the amplitude and phase information. Another possibility is the a scheme employing digital IQ detection where the IF (or the RF signal) is sampled directly by an ADC which usually samples alternating the real and imaginary components of the cavity. This of course requires correct timing of the data acquisition.

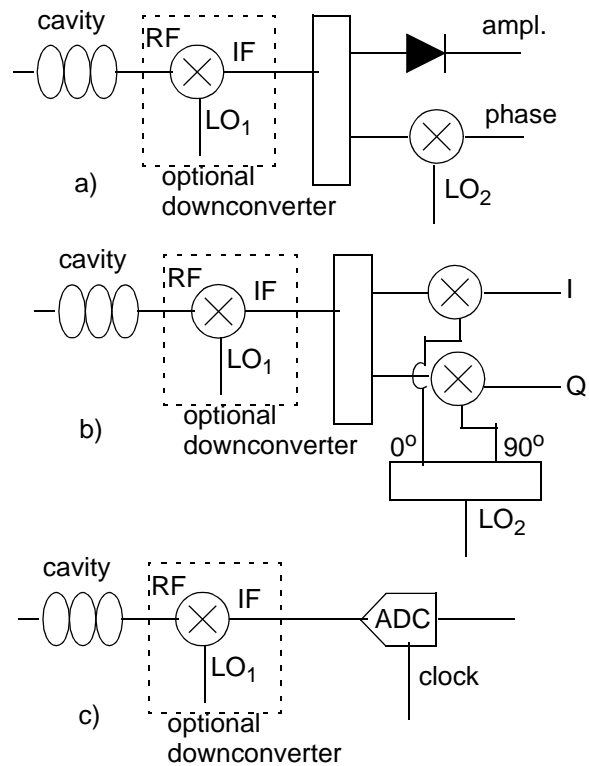


Figure 1: Field detection schemes. a) amplitude and phase detection, b) IQ detection, c) digital IQ detection.

With the rapid development of the telecommunication market industry had developed a variety of single chip solutions for amplitude detection, phase detection, and IQ detection based on analog multipliers. Examples are:

- AD8343 analog multiplier
- RF2411 analog multiplier
- AD8361 linear video detector (temperature stabilized)
- AD8302 logarithmic video detector and phase detector
- HMC 439 digital phase detector

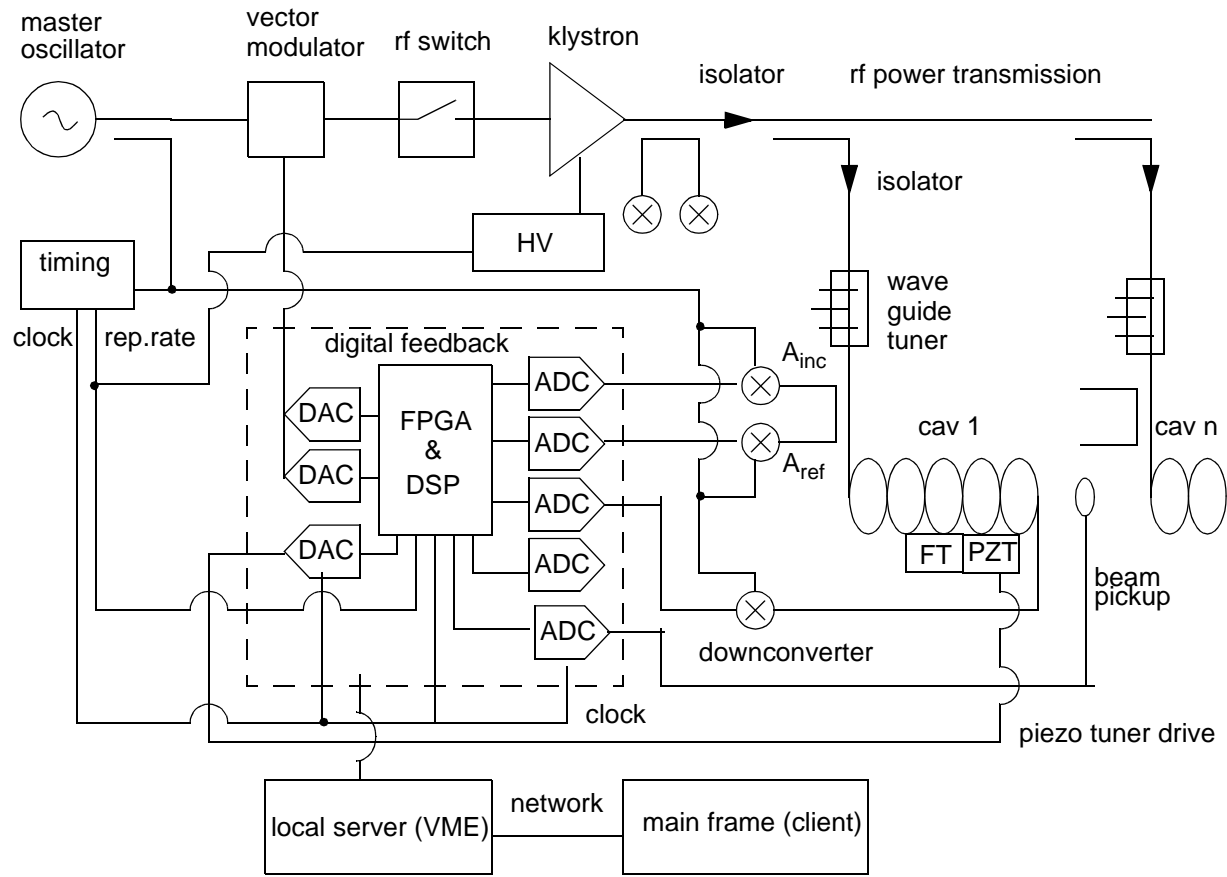


Figure 2: Typical configuration of an RF control system using digital feedback control.

- AD8347 IQ detector

The same circuits are also used to detect the incident wave and reflected wave vectors usually described as forward and reflected power. Examples of the excellent performance of these detectors are shown in Figure 3. The

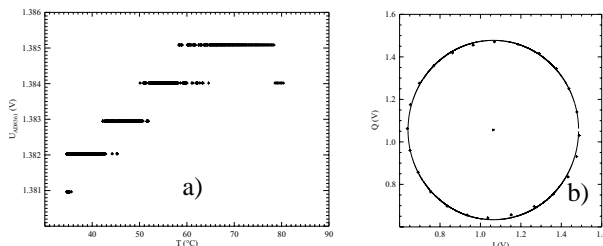


Figure 3: a) Temperature stability of the amplitude detector AD861 and b) linearity of IQ detector AD8347.

ACTUATORS FOR FIELD CONTROL

Similar circuits as used for field detection are also used for the control of the incident wave. Since analog multipliers can be also used for control of the amplitude of an rf wave they can be used in upconverters and for amplitude control. The digital downconversion scheme can also be used in an upconversion mode where the frequency f_1 (discrete

samples) written to the DAC which is clocked at f_2 generates a sideband (among many others) of f_1+f_2 which contains the control vector and is filtered and upconverted to the operating frequency of the cavity. Examples for vector modulators are:

- RF 2480
- AD8346
- HMC 495 and 497

The linearity of a vector modulator is shown in Figure 4.

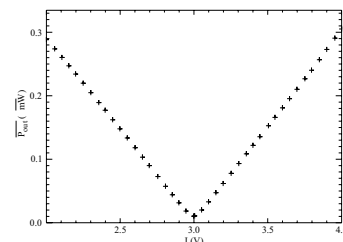


Figure 4: Linearity of the vector modulator RF 2480.

DIGITAL RF CONTROL

The key elements of a digital feedback system are the ADCs for the measurement of the detector signals for the cavity field and forward and reflected power, the DACs

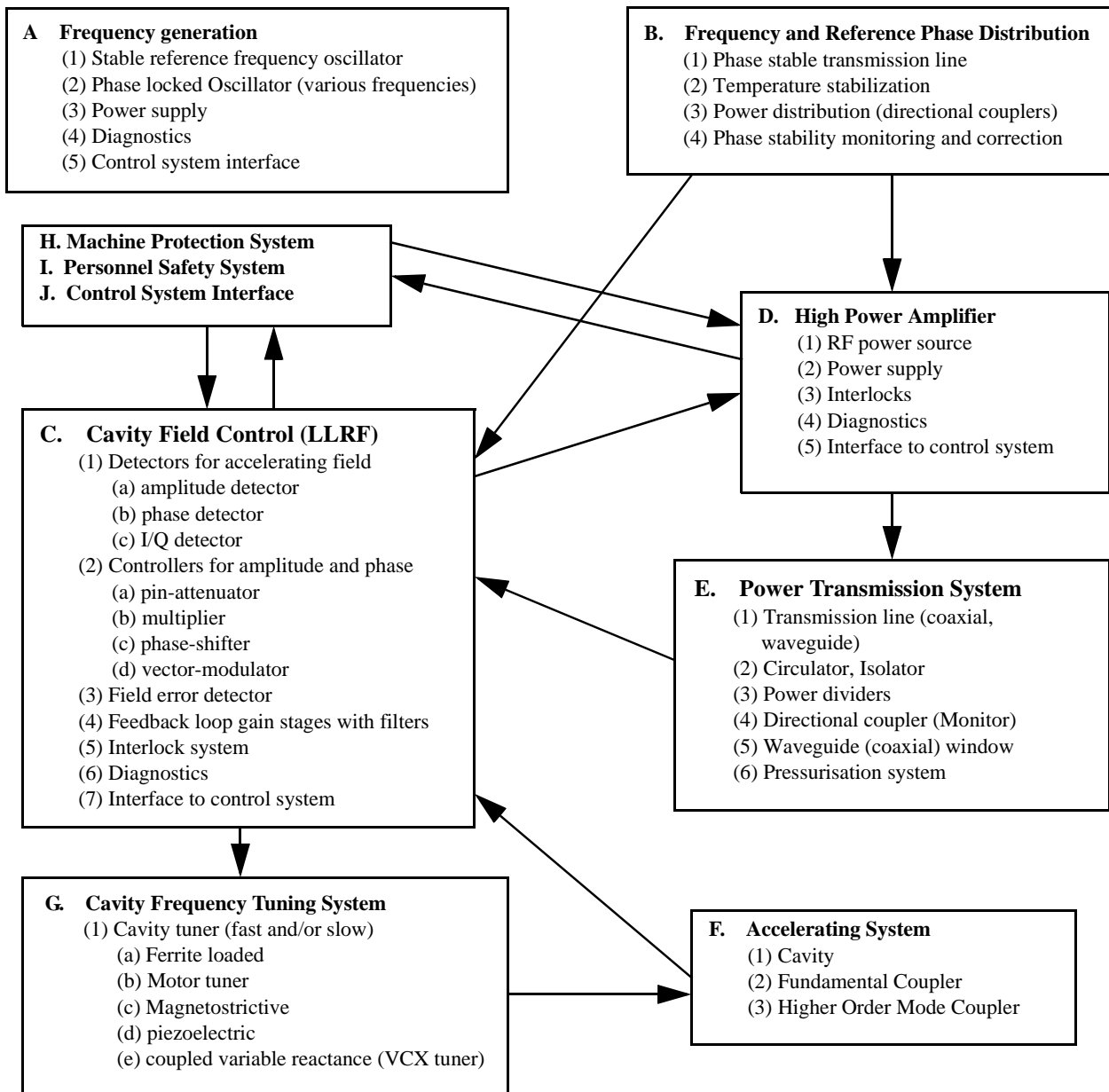


Figure 5: Breakdown of RF Control Subsystems and some choices for implementation.

which drive the actuators for field control, and the signal processing unit(s). The signal processing is performed by powerful FPGAs and DSPs allow low latencies from ADCs clock to DAC output ranging from a few 100ns to several μ s depending on the chosen processor and the complexity of the algorithms. Gigabit Links the high data rates between a large number of analog IO channels and the digital processor as well as for communication between various signal processing units. Typical parameters for the ADCs and DACs are a sample rate of 65-125 MHz at 14 bit resolution (example AD6644). For the signal processing one has the choice of FPGAs with several million gates, including many fast multipliers cores and even with power PCs on the same chip such as Virtex2Pro from Xilinx or the Stratix GX from Altera. More complex

algorithm are implemented on slower floating point DSPs such as the C6701 from Texas Instruments or the Sharc from Analog Devices. Typical configurations of the digital feedback hardware can be documented in [1-21].

ALGORITHMS AND PROCEDURES

The algorithms and procedures implemented in the digital feedback system should support automated operation with minimal operator intervention. A list of possible algorithms is shown figure 6. The feedback algorithms should be optimized for best field stability (i.e. lowest possible rms amplitude and phase errors) while being robust against parameter variations, allow for fast trip recovery, and support exceptional handling routines. Beam based

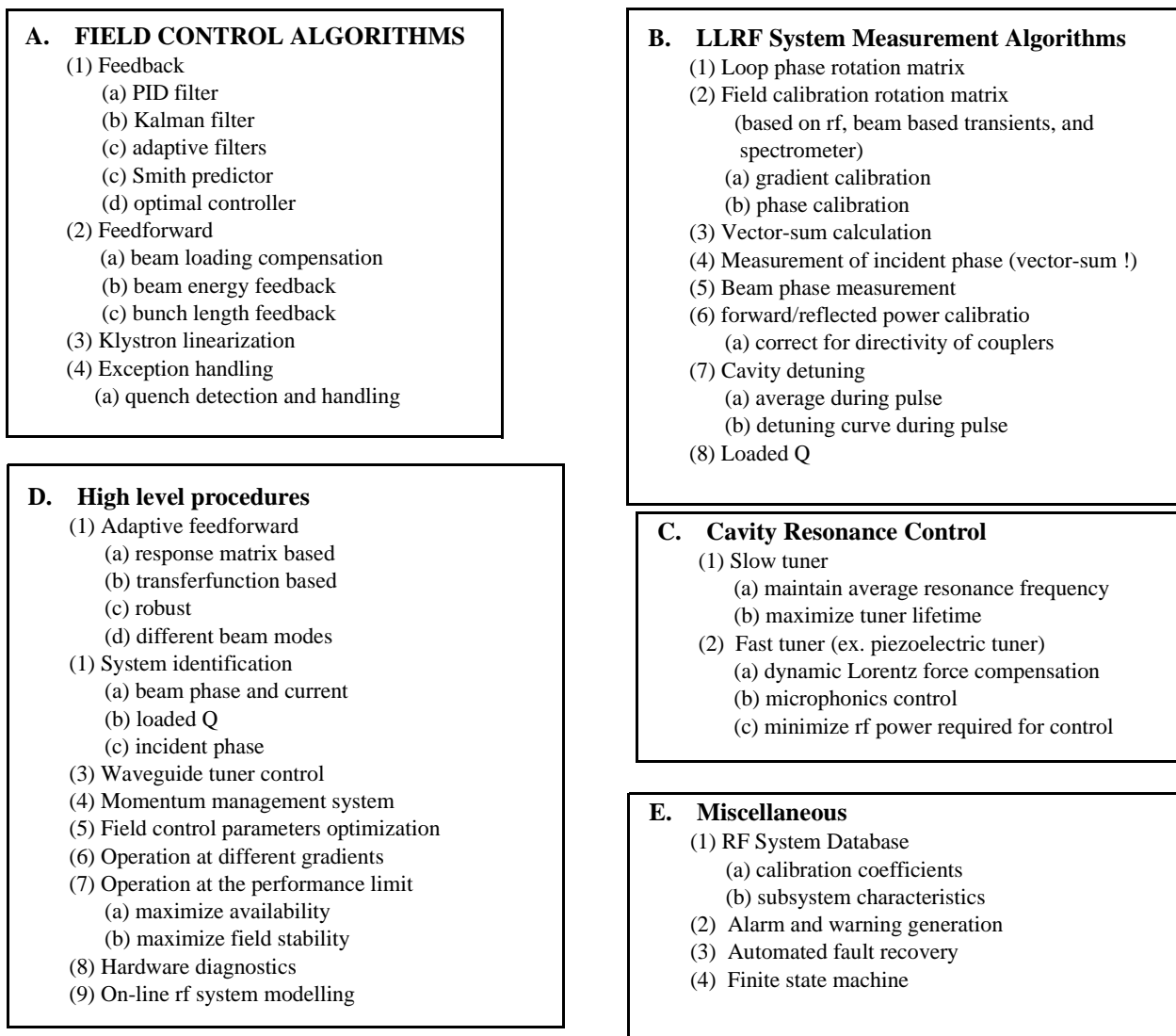


Figure 6: Algorithms and procedures required for an automated digital feedback system.

feedforward will further enhance the field stability. Also important is the automated control of the resonance frequency of the cavities with slow motor controlled tuners and fast piezo actuator based tuners for Lorentz force compensation in pulsed rf systems.

REFERENCE FREQUENCY SYSTEM

With the increasing demands on the emittance and bunch length of the electron bunches for linear colliders and X-FELs the requirements for amplitude and phase stability of the accelerating fields have also become more stringent. Frequency distribution systems for linear colliders must provide a phase stability of better than 1 ps while X-FELs may require as much as 10 fs stability. This seems feasible with a combination of fiber laser oscillator and actively stabilized fiber optic distribution systems. This level of stability has been demonstrated successfully in the lab

environment and is expected to be available in accelerator within the next 2 years.

SUMMARY

The rapid advances in digital technology allows the designer of an rf control system to employ real time digital feedback control with latencies in the range of a few hundred ns to a few μ s at sampling frequencies of up to 100 MHz at 14-bit resolution which is sufficient for regulation to the $1e-4$ level for amplitude and better than 0.1 deg. for phase. The powerful signal processing capability of FPGAs and DSPs support the implementation of complex algorithms which support a high degree of automation of operation. Recently a large number of detectors and actuators for amplitude, phase and in-phase and quadrature-phase (IQ) components, and up- and downconverters have been developed which simplify the design of the field

detectors drastically while guaranteeing low noise performance. These detectors are usually based on analog multipliers using Gilbert cell technology. In the area of low noise oscillators and highly phase stable rf reference frequency distribution system the application of laser oscillators and actively stabilized fiber distribution system it is expected that short and long term stabilities of the order of some 10 fs will be achieved in the next years.

REFERENCES

- [1] S.N. Simrock, "Achieving Phase and Amplitude Stability in Pulsed Superconducting Cavities", Proceedings of the 2001 Particle Accelerator Conference, Chicago
- [2] M. Liepe, S. Belomestnykh, J. Dobbins, R. Kaplan, C. Strohman, LEPP, Cornell, "A New Digital Control System for CESR-c and the Cornell ERL", Proceedings of the 2003 Particle Accelerator Conference, Portland
- [3] A. Regan et al., "The SNS Linac RF Control System", Proceedings of the 2002 Linac Conference, Gyeongju, Korea
- [4] M. Champion et al., "The Spallation Neutron Source Accelerator Low Level RF Control System", Proceedings of the 2003 Particle Accelerator Conference, Portland
- [5] A. Regan et al., "Newly Designed Field Control Module for the SNS", Proceedings of the 2003 Particle Accelerator Conference, Portland
- [6] L. Doolittle et al., "Operational Performance of the SNS LLRF Interim System", Proceedings of the 2003 Particle Accelerator Conference, Portland
- [7] K. Fong et al., "RF Control System for ISAC II Superconducting Cavities", Proceedings of the 2003 Particle Accelerator Conference, Portland
- [8] T. Plawski, T. Allison, J. Delayen, C. Hovater, T. Powers, "Low Level RF System for Jefferson Lab Cryomodule Test Facility", Proceedings of the 2003 Particle Accelerator Conference, Portland
- [9] S. Michizono et al., "Digital RF Control System for 400-MeV Proton Linac of JAERI/KEK Joint Project", Proceedings of the 2002 Linac Conference, Gyeongju, Korea
- [10] A. Büchner, F. Gabriel, H. Langenhagen, "Noise Measurements at the RF System of the ELBE Superconducting Accelerator", Proceedings of the 2002 EPAC Conference, Paris, France
- [11] T. Naito, K. Ebihara, M. Suetake, E. Ezura, "RF Reference Distribution Using Fibre-Optic Links for KEKB Accelerator", Proceedings of the 2001 Particle Accelerator Conference, Chicago
- [12] C. Hovater et al., "RF System Development for The CEBAF Energy Upgrade", Proceedings of LINAC 2002, Gyeongju, Korea
- [13] I. H. Yu et al., "The Low Level RF System for 100MV Proton Linac of KOMAC", Proceedings of the 2003 Particle Accelerator Conference, Portland
- [14] R. Wilcox, L. Doolittle, J.W. Staples, "A Fiber Optic Synchronization System for LUX", Proceedings of the 2004 EPAC Conference, Lucerne, Switzerland
- [15] A. Rohlev, J. Broere, R. Garoby, I. Kozsar, J. Serrano, "All Digital IQ Servo-system for CERN Linacs", Proceedings of the 2004 EPAC Conference, Lucerne, Switzerland
- [16] M. Huening, P. Bauer, G.W. Foster, "Simulation of RF Control of a Superconducting Linac for Relativistic Particles", Proceedings of the 2004 EPAC Conference, Lucerne, Switzerland
- [17] M. Laverty, S. Fang, K. Fong, "TRIUMF ISAC II RF Control System Design and Testing", Proceedings of the 2004 EPAC Conference, Lucerne, Switzerland
- [18] D. Valuch, H. Frischholz, J. Tuckmantel, C. Weil, "First Results with a Fast Phase and Amplitude Modulator for High Power RF Application", Proceedings of the 2004 EPAC Conference, Lucerne, Switzerland
- [19] J. Knobloch, A. Neumann, "RF Control of the Superconducting Linac for the BESSY FEL", Proceedings of the 2004 EPAC Conference, Lucerne, Switzerland
- [20] S. Michizono et al., "Control of Low Level RF System for J-Parc Linac", Proceedings of the 2004 Linac Conference, Luebeck Germany
- [21] J. Mourier et al., "Low Level RF Including a Sophisticated Phase Control System for CTF3", Proceedings of the 2004 Linac Conference, Luebeck Germany