DIGITAL LOW-LEVEL RF CONCTROLS FOR FUTURE SUPERCONDUCTING LINEAR COLLIDERS

S.N. Simrock, DESY

Abstract

The requirements for RF Control Systems of Superconducting Linear Colliders are not only defined in terms of the quality of field control but also with respect to operability, availability, and maintainability of the RF System, and the interfaces to other subsystems. The field control of the vector-sum of many cavities driven by one klystron in pulsed mode at high gradients is a challenging task since severe Lorentz force detuning, microphonics and beam induced field errors must be suppressed by several orders of magnitude. This is accomplished by a combination of local and global feedback and feedforward control. Sensors monitor individual cavity probe signals, and forward and reflected wave as well as the beam properties including beam energy and phase while actuators control the incident wave of the klystron and individual cavity resonance frequencies. The operability of a large llrf system requires a high degree of automation while the high availability requires robust algorithms, redundancy, and extremely reliable hardware. The maintenance of the llrf demands sophisticated on-line diagnostics for the llrf subsystems to minimize downtime.

INTRODUCTION

With the "cold" technology decision of August 19, 2004 accomplished, the global particle physics community has come together to begin developing a design for the proposed International Linear Collider. While the conceptual and detailed design for the linear collider will be developed in the next 3 years, most parameters of the rf system are sufficiently well known to be able to develop a conceptual design for the low level rf control systems. Low level rf systems are required for

- electron source (rf gun) and positron source (capture section)
- injector
- damping rings
- main linacs including bunch compressors
- crab cavities for beam delivery

The largest RF System installation will be in the main linacs with around 10,000 cavities in each linac where 36 cavities are driven by one 10 MW klystron. The technology for controlling the vector-sum of many cavities driven by one klystron has been demonstrated successfully at the TESLA Test Facility at DESY and is presently under commissioning for the VUV-FEL at DESY. It is a fully digital system providing the capability of feedback and feedforward, exception handling and extensive build-in diagnostics. However the full potential of such systems in terms of operability in large scale systems and the reliability required for the linear collider remain to be demonstrated. Currently a large number of sophisticated digital rf control systems are under construction in development. The descriptions of these designs that have been developed recently for various accelerator projects can be found in [1-15].

INTERNATIONAL LINEAR COLLIDER

The baseline machine should fulfill the following requirements:

- The maximum centre-of-mass energy should be 500 GeV with an energy range for physics between 200 GeV and 500 GeV.
- Luminosity and reliability of the machine should allow the collection of approximately L_{eq} = 500 fb^{-1} in the first four years of running.
- The collider has to allow for energy scans at all centre-of-mass energy values between 200 GeV and 500 GeV. The time needed for the change of energy values should not exceed about 10% of the actual data-taking time.
- Beam energy stability and precision should be below the tenth of percent level, in the continuum as well as during energy scans.

The strong likelihood that there will be new physics in the 500   1000 GeV range means that the upgradeability of the LC to about 1 TeV is the highest priority step beyond the baseline.

- The energy of the machine should be upgradeable to approximately 1 TeV.
- The luminosity and reliability of the machine should allow the collection of order of 1 ab^{-1} (equivalent at 1 TeV) in about 3 to 4 years.

LINAC RF SYSTEM PARAMETERS

The main linacs of the linear collider accelerate the electron and positron beams from the damping rings from 5 GeV to 250 GeV. The acceleration is achieved by around 10,000 cavities operated close to 25 MV/m. The main rf system parameters are listed in Table 1. The main linacs are based on 1.3 GHz superconducting technology operating at 2 K. The cryoplant, of a size comparable to that of the LHC, consists of seven subsystems strung along the machines every 5 km. RF accelerator structures consist of close to 21,000 9-cell niobium cavities operating at gradients of 23.8 MV/m (unloaded as well as beam loaded for

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500 GeV c.m. operation. These cavities are supplied with rf power in groups of 36 by 572 10 MW klystrons and modulators. The rf pulse length is 1370 µs and the repetition rate is 5 Hz. At a later stage, the machine energy may be upgraded. The upgrade will be achieved by raising the number of klystrons to 1212 and reducing the repetition rate to 4 Hz. The capacity of the original cryoplant will be doubled.

Table 1: Main Linac RF System Parameters

Parameter	Units	Value
Accelerating Gradient (Loaded)	MV/m	23.4
RF Frequency	GHz	1.3
Repetition Rate	Hz	5
No. Bunches / Train		2820
Bunch Spacing	ns	337
Bunch charge	10^10	2
Active Length	km	21.8
Number of cavities / linac		~10,000
Number of cavities / klystron		36
Number of klystrons / linac		286
Power / klystron	MW	10
Power / cavity	kW	200

REQUIREMENTS FOR RF CONTROL

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.

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. The main linacs of the ILC require tight field control of the order of 0.1% for the amplitude and 0.1 deg. 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 deg. 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.

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.

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.

SOURCES OF PERTURBATIONS

The major sources of perturbations which have to be controlled by the low level RF system are fluctuations of the

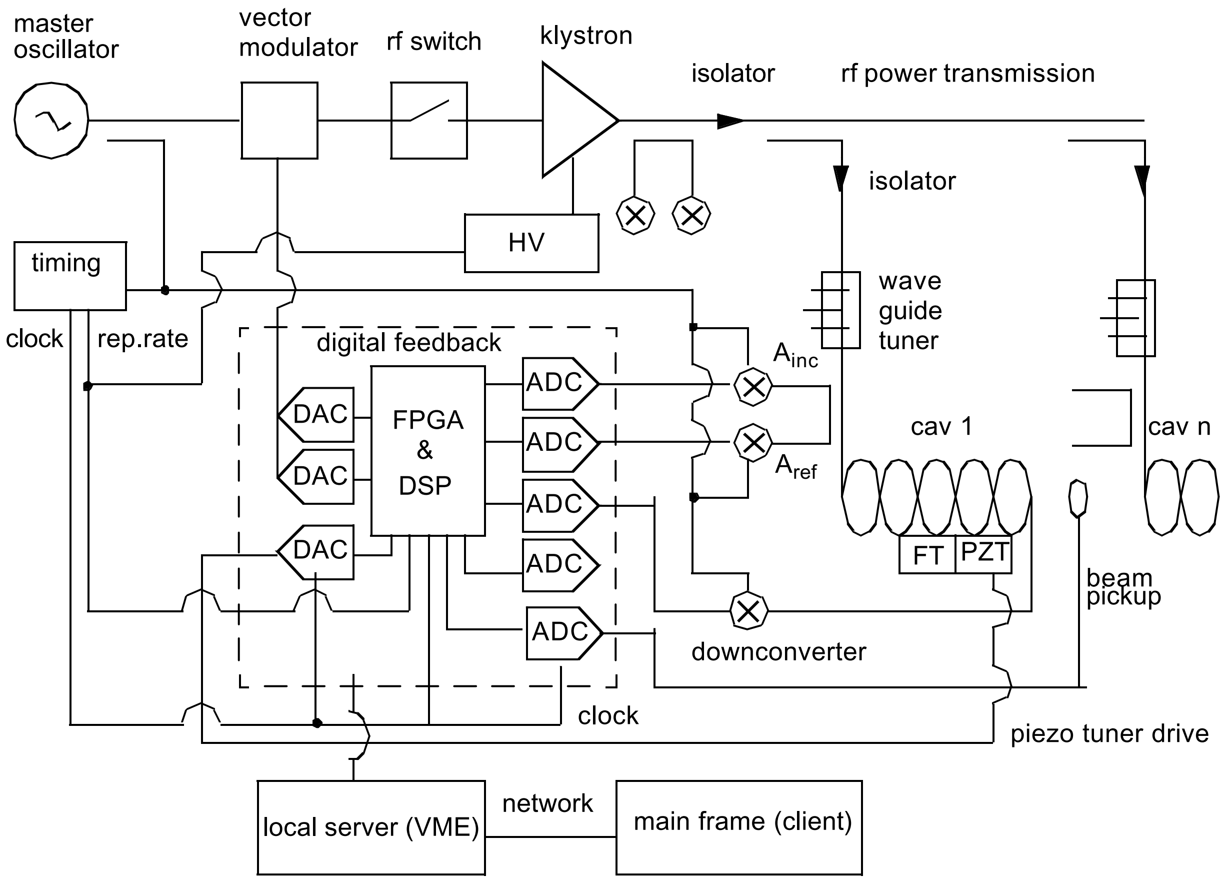

Figure 1: Typical configuration of an RF control system using digital feedback control.

resonance frequency of the cavities and fluctuations of the beam current. Changes in resonance frequency result from deformations of the cavity walls induced by mechanical vibrations (microphonics) or the gradient dependent Lorentz force.

CONTROL CONCEPTS

The basic options for driving a cavity are the self-excited loop (SEL) and the generator driven resonator (GDR). The conditions for operation of the SEL are a loop gain >1 and a loop phase shift of multiple of 360 deg. which can be set by the loop phase shifter. Therefore the SEL will operate at the cavity resonance frequency without the need for an external generator. A power limiter is necessary to protect cavity and coupler from excessive power. An amplitude feedback loop will maintain a stable gradient while phase lock with respect to an external reference can be achieved by use of. For the rf system for the ILC the GDR system is preferred because the microphonics is much smaller than the cavity bandwidth and allows for amplitude and phase feedback during filling to ensure stable field conditions at the begin of the beam pulse.

Control Algorithm

The basic feedback mechanism is based on a proportional controller which can be supplemented by a integrator to further reduce the residual errors. In the pulsed operation the use of an integrator must be carefully evaluated since steady state might never be reached during the pulse and the integrator might introduce a slope on cavity gradient and phase. Since the dominating sources of perturbations such as beam loading and Lorentz force detuning are of repetitive nature, a feed forward system will already reduce most of the errors efficiently. Slow variations in RF system parameters dictate an adaptive feed forward system which corrects for these slow drifts.

Other RF Control Issues

The designer of a low level RF control system must decides whether to use Amplitude and Phase (A&P) or Inphase and Quadratur-phase (I/Q) detectors and controllers and whether the system should be implemented with analog or digital technology or as a hybrid system. While the I/Q concept allows for detection and control in all 4 quadrants including zero, is naturally better for control of cavity detuning (Q control already reduces the amplitude error) and is best for correction of large errors (best decoupling of control loops), the amplitude detector has the advantage of lower noise levels and can support control to the 10-4 level and is also more intuitive for operators who are used think in terms of amplitude and phase. It is also easier to design a power limiter for the drive signal of an

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A. FIELD CONTROL ALGORITHMS
(1) Feedback
(a) PID filter
(b) Kalman filter
(c) adaptive filters
(c) Smith predictor
(d) optimal controller
(2) Feedforward
(a) beam loading compensation
(b) beam energy feedback
(c) bunch length feedback
(3) Klystron linearization
(4) Exception handling
(a) quench detection and handling

B. LLRF System Measurement Algorithms
(1) Loop phase rotation matrix
(2) Field calibration rotation matrix
(based on rf, beam based transients, and spectrometer)
(a) gradient calibration
(b) phase calibration
(3) Vector-sum calculation
(4) Measurement of incident phase (vector-sum !)
(5) Beam phase measurement
(6) forward/reflected power calibratio
(a) correct for directivity of couplers
(7) Cavity detuning
(a) average during pulse
(b) detuning curve during pulse
(8) Loaded Q

C. Cavity Resonance Control
(1) Slow tuner
(a) maintain average resonance frequency
(b) maximize tuner lifetime
(2) Fast tuner (ex. piezoelectric tuner)
(a) dynamic Lorentz force compensation
(b) microphonics control
(c) minimize rf power required for control

D. High level procedures
(1) Adaptive feedforward
(a) response matrix based
(b) transferfunction based
(c) robust
(d) different beam modes
(1) System identification
(a) beam phase and current
(b) loaded Q
(c) incident phase
(3) Waveguide tuner control
(4) Momentum management system
(5) Field control parameters optimization
(6) Operation at different gradients
(7) Operation at the performance limit
(a) maximize availability
(b) maximize field stability
(8) Hardware diagnostics
(9) On-line rf system modelling

E. Miscellaneous
(1) RF System Database
(a) calibration coefficients
(b) subsystem characteristics
(2) Alarm and warning generation
(3) Automated fault recovery
(4) Finite state machine

Figure 2: Algorithms and procedures required for an automated digital feedback system.

A&P controller than for an I/Q controller. More issues that need to be considered by the LLRF designer are:

- Control of the cavity resonance frequency. Here the critical issues 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 pulse 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.
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- Operation close to klystron saturation will result in strong dependency of loop gain with klystron output power.
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- 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.

RF CONTROL SYSTEM ARCHITECTURE

The architecture of a typical RF control system is shown in Figure 1. 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.

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 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 µs 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 are documented in [1-15].

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 2. 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 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.

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 µs at sampling frequencies of up to 100 MHz at 14-bit resolution which is sufficient for regulation to the 1e-3 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.

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