LLRF SYSTEMS FOR MODERN LINACS: DESIGN AND PERFORMANCE

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Abstract

Near-future linac projects put yet unreached requirements on the LLRF control hardware in both performance and manageability. Meeting their field stability targets requires a clear identification of all critical items along the LLRF control loop as well as knowledge of fundamental limitations. Large-scale systems demand for extended automation concepts. The experience gained with present systems as well as dedicated experiments deliver the basis for a design of future systems. Digital hardware has evolved quickly over the past years and FPGAs became common not only in LLRF control. A high degree of digitization in various fields, as for example beam diagnostics, suggests to aim for a convergence of the digital platform designs. Channeling of efforts of different research laboratories may be the key to an affordable solution that meets all requirements and has a broad range of applications.

LINAC DESIGN CHOICES

Prior to the design of the LLRF goes the design of the linear accelerator and many of its design choices affect the design of the LLRF.

The choice between normal- or superconducting resonators has an impact on the design of the LLRF system. Two typical time-constants are of interest when designing the LLRF system, the time-constant of the resonator (nc: $\sim 1\,\mu$s, sc: ~ 1 ms) and the total round trip time in the LLRF loop including actuators and sensors (typically a few μs). In a pulsed system, the pulse-length if of importance additionally.

The relation between the time-constant of the resonator and the total round trip time in the loop affects the choice of the real-time controller. A small time-constant will prevent from high proportional gains, and under certain circumstances, real-time feedback may not be desired. If on the other hand if the time constant of the resonator is short compared to the pulse length, the behaviour will be dominated by the transient response of the cavity.

Pulsed systems are usually more complex than continuous wave (cw) systems. Pulsed systems have to deal with transient effects and repetitive error contributions as from Lorentz force detuning. LLRF for cw systems deals with transient effects only during startup. Complicated pulse structures can require for a large dynamic range of the control system and its analog frontends.

Linacs are built for various purposes with different requirements on the field stability. While for collider experiments the requirements are rather relaxed, they can be of the order of 10^{-4} in amplitude and $0.01°$ in phase in case of FELs. The field requirements set the limits for the noise figures of the LLRF components as master oscillator, sensors and actuators. Especially in user-facilities, the LLRF-system is exposed to requirements beyond field stability, namley the operability and availability of the machine. Since user facilites offer defined time-slots, it is crucial that all subsystems, indluding the LLRF system, behave as expected during that time. This requires for a design with extended maintenance capabilities as well as intelligent automation schemes for the operation of LLRF.

LLRF DESIGN CHOICES

Inter- or Intra-Pulse Feedback

For pulsed system, the feedback can calculate corrections on the drive signal within the pulse or between pulses (Fig. 1).

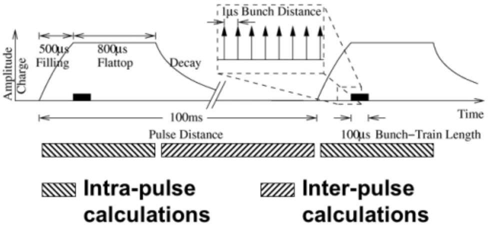

Figure 1: Intra- and inter-pulse feedback

An intra-pulse feedback is appropriate if the time-constant of the resonator is long compared to the total round-trip time in the loop. For digital systems, the intra-pulse feedback puts higher performance requirements on the processing hardware than inter-pulse feedback, since the time between subsequent calculations of corrections is typically in the MHz-range. The calculation time itself has to be low compared to the round-trip time in the loop that originates from analog components in order to be able to run appropriate gains in the loop. For inter-pulse feedback the calculation-time is limited only by the time between subsequent pulses.

A/ϕ or I/Q

The choice of the coordinate system affects the behavior of the control algorithm, which is usually given by a linear transfer function. The advantage of amplitude-phase (A/ϕ) control lies in the fact that the direction of A/ϕ-feedback is invariant under rotations along the control loop. Controllers based on cartesian coordinates (I/Q) are exposed to instabilities in the presence of phase-rotations along the control loop if no further measures are taken. On the other hand, I/Q-control is capable of dealing with a larger dynamic range, while for the A/ϕ-control the phase is rarely defined for small amplitudes leading to unwanted $360\,°$-discontinuities at the feedback signal.

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Single Cavity or Vector-Sum

Cost-reduction is the major advantage of combining several cavities into a single vector-sum, i. e. driving more than one cavity by a single rf amplifier that is controlled by a single LLRF system. Along with the introduction of vector-sums goes an extended sensitivity to constant offsets. Offsets occur as calibration errors of individual channels, non-linear effects and crosstalk. In the presence of (uncorrelated) microphonics, constant (or quasi-constant) errors on individual channels lead to time-varying errors on the vector-sum of all channels. Therefore, vector-sums require linear and crosstalk-free sensors as well as a higher level of maintenance. Procedures for the calibration of the channels can involve the analysis of beam-induced transients.

GDR or SEL

Resonators are driven by amplified rf-signals. The actuator, e. g. a vector-modulator, modifies the rf-signal according to the output of the controller. The origin of the rf-signal that is amplified on its path to the resonator can either be supplied by an external source (usually the master oscillator) or originate from the resonator itself. The former case is referred to as generator driven (gdr) while the latter is a self-excited loop (sel). The advantage of the sel lies in the fast catching of the resonance frequency of the system, since the self-excitation guarrantees that the cavity is always driven with its momentary center frequency. This is, for example, a very interesting feature for systems where the resonance frequency changes with the heat-load of the resonator. A gdr system has the advantage that the resonator is at a defined phase already on startup. If starting from noise, it is in principal possible that the sel is locking on a mode different from the desired one.

A sel can be created from a system that is set up as the gdr in Fig. 2 by means of a (digital) controller with the appropriate software and an analog frontend with a sufficient bandwidth. In fact, a mode is self-excited in a generator-driven system just by rotating the phase for this mode by π. This allows for hybrid systems with a smooth transistion between the sel and the gdr part.

Analog or Digital

Under certain circumstances, analog systems may be preferable compared to digital ones. Analog systems are superior in terms of delay but lack of flexibility. They are the system of choice if the LLRF-system is expected to be built once and not subject to further changes. If flexibility and a performance close to technical limits is required, digital systems are preferred. These require more resources in terms of cost and manpower but offer flexibility and entry points for diagnosis. The possibilty of complex pulse-patterns or the successful control of vector-sums is owed to the flexibility of digital systems.

Due to its complexity, digital rf control requires devices that are at the high-end scale of todays market situation. Usually, field programmable gate arrays (FPGA) are used rather than digital signal processors (DSP) due to their very low latency. The implementation of a vector-sum in an FPGA consumes more than 50% of the resources of current FPGA chips. Since the performance of FPGAs is increased on a monthly basis and the fact that FPGAs are a relatively young technology, further improvement (and price reduction) of these devices is expected.

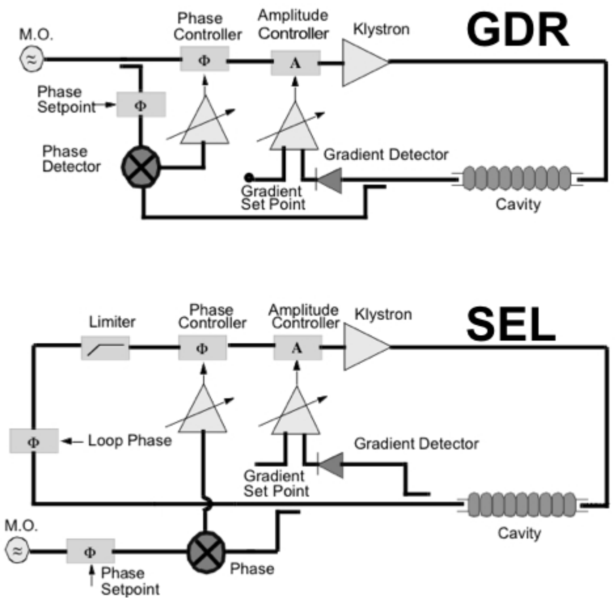

Figure 2: Structure of a generator drive loop (gel) and a self excited loop (sel).

System Integration

Integration and communication between subsystems is crucial not only in large-scale accelerators. Presently, subsystems communicate via direct cable connections, local bus systems (typically VME/VXI) or ethernet moderated by a computing unit that is attached to a local bus. The choice for a bus-system affects not only the LLRF, however, the LLRF system is putting the highest data-rates on the bus compared to other subsystems. Besides its performance, the price and long-term support by industry is of importance. VME/VXI systems are on the down slope but still supported. New, not yet established systems with a high performance undergo the risk of unpredictable developments in the market. As an alternative to industrial bus-systems custom developed systems can be interesting. Further, since some modern FPGA solutions contain on-board processors suitable for Unix-like operating systems, the integration of the whole LLRF system with ethernet connection can be considered.

Platforms

The scheme rf-input, downconversion, digital data processing, dc- or if-output is widely spread in accelerator physics. Modern LLRF design takes this into account. The VPC-board from the Paul Scherrer Institute is designed as a general-purpose board with applications not only in LLRF, [1]. The applications of programmable digital I/O processing hardware with analog frontends ranges from the evaluation of beam position and arrival monitors to beam-feedback systems and oscilloscope-functionality.

Master Oscillator and Distribution

All synchronization-critical subsystems of an accelerator are phase-locked to a reference, the master-oscillator. Since the loop-bandwidth of each subsystem is individually determined by the subsystem, the phase noise spectrum of the reference matters. Additionally, the transportation of the reference over the distances determined by the dimensions of the linac is subject to drifts caused by thermal expansion. Integrated phase jitter for a typical pill-box resonator is of the order of 70 fs at frequencies between 10 Hz and 10 MHz. Optical resonators can further reduce this downto 10 fs at high frequencies between 10 kHz and 20 MHz, [2]. The distribution of the reference under the conditions of low jitter demands for feedback systems that correct the phase on-line.

Much More

The presented items are only a fraction of modern LLRF design. The challenge of LLRF control is to precisely measure an process signals well below 1 V in the presence of the electromagnetic interference (EMI) caused by MW-amplifiers. Therefore, EMI-shielding as well as separation of channels is a main issue during LLRF design.

The issue of detuning in superconducting cavities caused by microphonics or Lorentz-forces is addressed by a number of research projects. Piezos seem to be suited for compensation, [3], [4].

Along with the design of the LLRF system goes the specification of the coupling of the resonators, which is not necessarily the so-called critical coupling since the power goes with $1 + (\Delta f / f_{1/2})^2$ where Δf is the detuning and $f_{1/2}$ the half-bandwidth. In some cases it may be desired to be able to change the coupling on demand.

A careful choice hat to be made for the intermediate frequency as well as for control algorithms which might contain algorithms for narrowing the loop bandwidth such as Kalman-filters.

MODERN LINACS AND PERFORMANCE

This section will give examples of LLRF systems that utilize different designs and give a rough estimate of their performance in terms of field stability.

The SNS proton accelerator is one of the few systems that run superconducting cavities in a pulsed (up to 60 Hz) operation. Key figures are: generator-driven, digital I/Q control with one FPGA-based control system per cavity. The performance is measured below 0.1% in amplitude and 0.1° in phase, [5].

The superconducting FLASH electron accelerator is the only system that drives up to 16 cavity (upgraded 32) by one rf amplifier with one control system. It is operated pulsed, controlled by multi-channel FPGA boards (partially still DSP) with proportional I/Q control. Short-term performance is below $5 \cdot 10^{-4}$ in amplitude and 0.07° in phase.

The TRIUMF ISAC Heavy Ion accelerator uses digital I/Q control. It utilizes a self-excited loop for a quick resonance tracking of its cavities. An separate feedback loop only for the resonance tracking adjusts the center frequency right befor phase feedback is activated, [6].

ELBE is one of the few examples that very successfully use analog control hardware. Originally designed for CW operation of superconducting cavities it has proven to support even pulsed operation, [7]. The measured energy spread is well below 0.5%.

The pulsed SCSS prototype accelerator has a digital I/Q control system for each of its normal conducting cavities. It has short bunch-trains, which would make a real-time feedback inefficient. Therefore the digital control system calculates the wave-forms sent to the rf amplifiers in the gap between pulses.

SUMMARY

LLRF system development is a task with numerous free parameters that need to be fixed by the designer. Facing the requirements of modern and future accelerators, LLRF system development is anything but standard, it is rather a subject of reasearch. In many cases, the linear accelerator defines the boundaries within which system designer has to make his decisions, like pulsed/continuous wave or superconducting/normal conducting. Beyond the numbers given by the requiremed field stability, careful attention has to be payed to scale of the installation and operabilty issues aswell as cooperation with other subsystem that might use similar hardware.

A number of design choices have been presented along with some examples of linear accelerators that utilize different LLRF designs.

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