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Analog cavity simulator

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ABSTRACT

Most of the low-level radio frequency (LLRF) systems are being developed well before the machines are being set up and ready to be commissioned. Therefore it is imperative to be able to test and evaluate their functionality and performance in the laboratory, before the instrument is installed in the final configuration. Real accelerator cavities are very expensive and frequency-dependent, hence impractical for mass factory testing of instrumentation. As an alternative, we developed an analog cavity simulator. The article gives an explanation of the main design concept, some key considerations of its implementation in order to reach the required specifications, and presents the test results, showing the simulator performance.

1. Introduction

Transverse and longitudinal beam manipulation in a particle accelerator is a complex task affected by nearly all of its subsystems. Beam dynamics is a function of electromagnetic fields in RF structures. These fields are greatly influenced by cavity and RF instrumentation design. The primary control instrument for manipulation of those fields in RF structures such as accelerator cavities is referred to as the LLRF control system. A typical simplified design scheme of an LLRF system is presented in Fig. 1.

1.1. LLRF system

The LLRF system has evolved from analog amplitude and phase detector into a field programmable gate array (FPGA) based digital control system, that can handle multiple functions on multiple topologies while enabling the user to change processing algorithms. Every accelerator is specific and therefore it needs a specifically configured LLRF system. These systems differ in terms of design, implementation, and processing algorithms. Some examples of such systems that operate superconducting RF structures are the Libera LLRF system [1,2], the LLRF control system for the main LINAC of the International Linear Collider [3], and the MTCA.4 platform-based digital LLRF integrated control system primarily designed for the upcoming European X-ray free electron laser [4].

1.2. Accelerator RF cavity

Radio frequency structures that are relevant for the subject presented in this paper are denoted as RF cavities. They are usually operated as normal conducting structures or as superconducting structures. The basic principles of operation of both types are different, but they can be both modeled with similar parameters in regard to the electromagnetic fields propagating in them.

Each RF cavity has numerous resonant frequencies that correspond to electromagnetic field modes which satisfy the necessary boundary conditions on its walls. Only the TM010 mode is usually used for acceleration. The resonant frequency of this mode is usually called the center frequency and it is strictly locked to the cavity's geometry and therefore it is defined beforehand. Typical values of resonant frequencies for accelerator cavities range from a few MHz to up to tens of GHz. State of the art designs and manufacturing procedures allow accelerator cavities to have very high unloaded quality factor. Typical values range from a few tens of thousands for normal conducting cavities to up to 10^{10} for superconducting cavities [5,6].

In this paper we present a solution in the form of an analog cavity simulator (ACS), which emulates the key characteristics of a real accelerator cavity response.

2. Requirements

Design requirements for our simulator have been derived from three main considerations. These are the expected LLRF system

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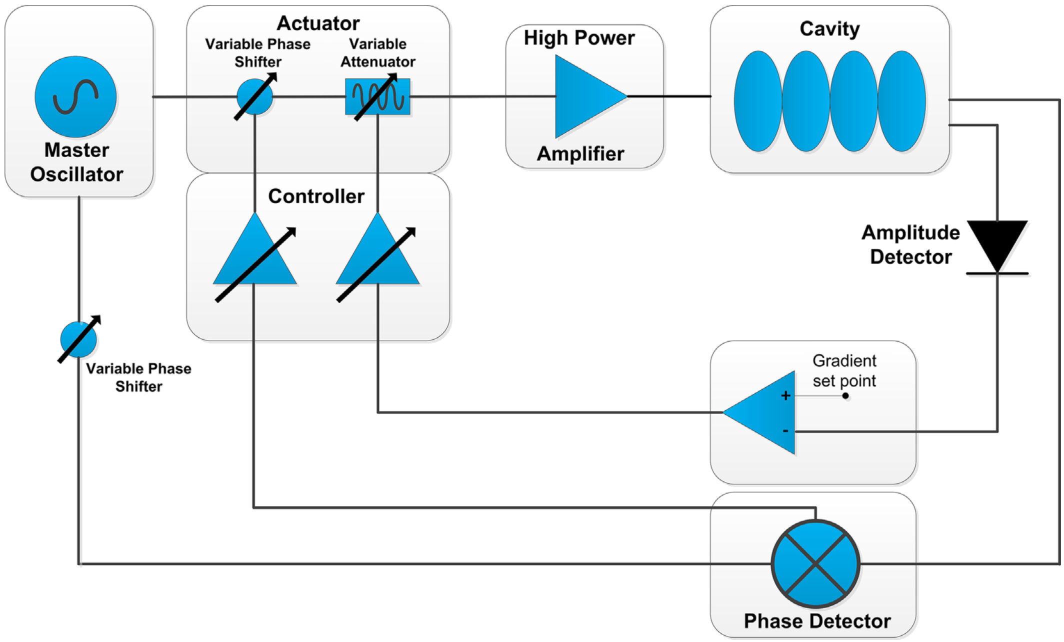

Fig. 1. Simplified scheme of a typical LLRF system.

performance, the accelerator cavity electrical model, and the need for low cost and high reproducibility.

2.1. LLRF system performance

The LLRF system relies on feedback and/or feedforward control loops. In order to achieve the desired effect on the beam, the RF fields have to be properly modified and stabilized at the exact time when the beam is present in the cavity independently of the RF source of the machine. RF sources can be pulsed or continuous-wave (CW). The LLRF system performance is usually evaluated in terms of amplitude and phase stability of the RF fields within the time window when the beam is present in the cavity. Amplitude and phase stability can be expressed in terms of out-of-loop noise measured at a certain frequency in a certain bandwidth. Today the strictest requirements for LLRF systems are in the range of a fraction of a percent or degree of both amplitude and phase. These strict performance requirements of the LLRF systems pose tight requirements in terms of noise, phase noise, and distortion for the cavity simulator. It is expected that the residual phase and amplitude noise of the cavity simulator has to be lower than the performance of the LLRF system that is being evaluated.

2.2. Accelerator cavity model

In microwave electronics the behavior of an accelerating structure at a certain mode can be modeled in terms of an electric circuit model composed of resistance, inductance and capacitance (RLC circuit). The fundamental mode, along with other modes (passband modes, higher-order modes, etc.), can be represented with its own RLC circuit [7]. Fig. 2 shows a typical cavity RLC circuit model for one such mode.

Such a circuit represents a band-pass filter from the high frequency electronics perspective [8]. Like accelerator cavities, band-pass filters are defined by the center frequency and the quality factor. Therefore we can use the center frequency and quality factor of an accelerator cavity as requirements for designing a band-pass filter.

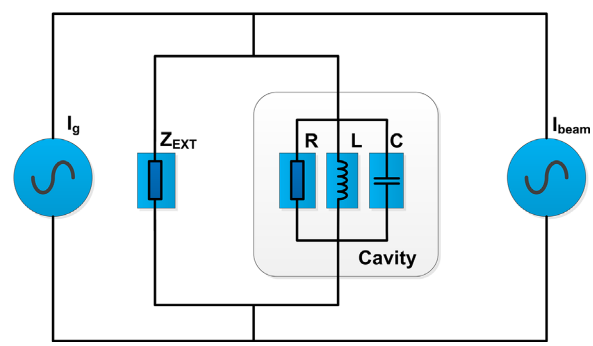

Fig. 2. Simplified circuit model of an accelerator RF cavity.

3. Cavity simulator design concept and implementation

An ultra-narrow band-pass filter response can be simulated in various ways. The simplest and the most straightforward solution is to build the exact RLC circuit as in Fig. 2 by using lumped elements. However, after making a quick calculation of the R, L, and C values (quality factor$=R/\sqrt{(L/C)}$; one possible solution for a quality factor of 10^7 is $R=1\times10^{12}\,\Omega$, $C=5.3\times10^{-20}$ F and $L=5.3\times10^{-16}$ H), it becomes obvious that such an approach is impractical. Similar limitations can be observed when using mixed structures of microstrip, lumped elements, and physical structures made of metallic or dielectric materials. The internal losses of such materials do not allow for high quality factor structures (above 10^6). Another way is to perform the cavity simulation in the digital domain using analog-to-digital converters (ADCs), FPGAs and digital-to-analog converters (DACs)[9]. With such an approach, very high quality factors can be achieved and the same hardware can be reused for various types of cavity simulation structures. The main disadvantage is the price in terms of production (high performance ADCs, FPGAs and DACs are very expensive) and in terms of programing resources (manpower). The digital approach also suffers from poor residual noise performance since the quantization noise of the ADCs and DACs limits the noise floor.