SOLID STATE DIRECT DRIVE RF LINAC: CONTROL SYSTEM

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Abstract

Recently a Solid State Direct Drive® concept for RF linacs has been introduced [1]. This new approach integrates the RF source, comprised of multiple Silicon Carbide (SiC) solid state Rf-modules [2], directly onto the cavity. Such an approach introduces new challenges for the control of such machines namely the non-linear behavior of the solid state RF-modules and the direct coupling of the RF-modules onto the cavity. In this paper we discuss further results of the experimental program [3] [4] to integrate and control 64 RF-modules onto a lambda/4 cavity. The next stage of experiments aims on gaining better feed forward control of the system and on detailed system identification. For this purpose a digital control board comprising of a Virtex 6 FPGA, high speed DACs/ADCs and trigger I/O is developed and integrated into the experiment and used to control the system. The design of the board is consequently digital aiming at direct processing of the signals. Power control within the cavity is achieved by an outphasing control of two groups of the RF-modules. This allows a power control without degredation of RF-module efficency.

MATERIALS AND METHODS

The system decomposition as shown in Figure 1 separates the system into two sub-systems, the control system and the cavity system (all block-diagrams are SysML [5] internal block diagrams (ibd)).

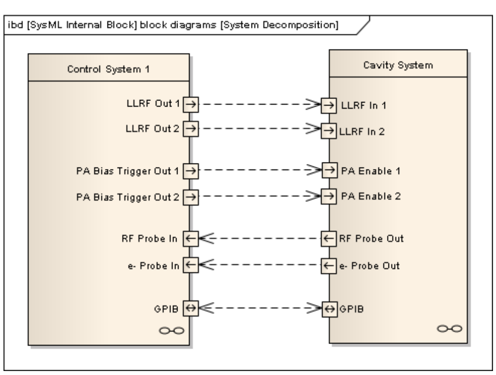

Figure 1: System Decomposition.

The cavity system (Figure 3) contains a 150MHz lambda/4 resonator that has a circumferential slot that separates the resonator into two conducting parts electrically isolated from each other. The current on the inner resonator wall is driven by a number of RF-modules each of which utilizing 8 SiC transistors in a parallel push-pull configuration for amplification of the drive signal. The power for the pulsed operation of the RF-modules is stored in a capacitor bank on the RF-module that is charged by a high voltage power supply unit (HVPSU). The charging voltage can be controlled by the control software. The drive signal for the transistors on the RF-modules comes from a pre-amplifier stage (PA) that amplifies the low level RF (LLRF) signal, splits and phase-shifts the amplified signal and adds a bias voltage to each output thus providing two (± 180) drive signals for each RF-module. The operation point of each PA has to be set with a trigger pulse that starts before the LLRF arrives and stops after it. A calibrated antenna measures the electrical field in the cavity and is also able to detect currents caused by field emission, multipacting, ionization effects and field break-downs. We grouped the RF-modules into two groups allowing individual LLRF signals for each RF-module group (for reasons described later).

The first stage of experiments focused on demonstrating power combining and stable operation of the RF-modules on the cavity. Results with 32 RF-modules have been published in [3] and [4]. Since then the experiment has been moved to a new bunker and upgraded to run with 64 RF-modules in order to achieve higher electrical fileds within the cavity.

The analog control system for driving these experiments is depicted in Figure 2. It uses an Agilent N5181A MXG Analog Signal Generator to provide an RF-pulse with a certain frequency and amplitude set by the control software. The length of the RF-pulse is controlled by a trigger. The signal is split up in order to provide both (identical) LLRF output signals. The NI-Rack is a National Instruments (NI) PXI-1042Q chassis that hosts the control computer (NI PXI-8110 controller) and the timing system (NI PXI-7851R FPGA and NI PXI-6653 timing module). The timing system provides a clock signal and freely programmable triggers with 25ns resolution. The two oscilloscope are LeCroy Wave Runner 104MXi-A. Scope1 is software controlled and serves as a data acquisition device, the LLRF signal and the probe signals can be read by the control software. Scope2 independently of the control system software shows control signals from the system. The custom made breakout box optically decouples the NI rack from the experiment.

Figure 5 illustrates the control software concept. A LabVIEW [6] program with a graphical user interface (GUI) has been used for controlling the experiment. It takes care of all configuration and persistent data storage issues. Interactive operation of all software controlled devices can be achieved by device specific dialogs. The configuration scheme of the program allows it to easily add extensions (applications) that perform automated tasks.

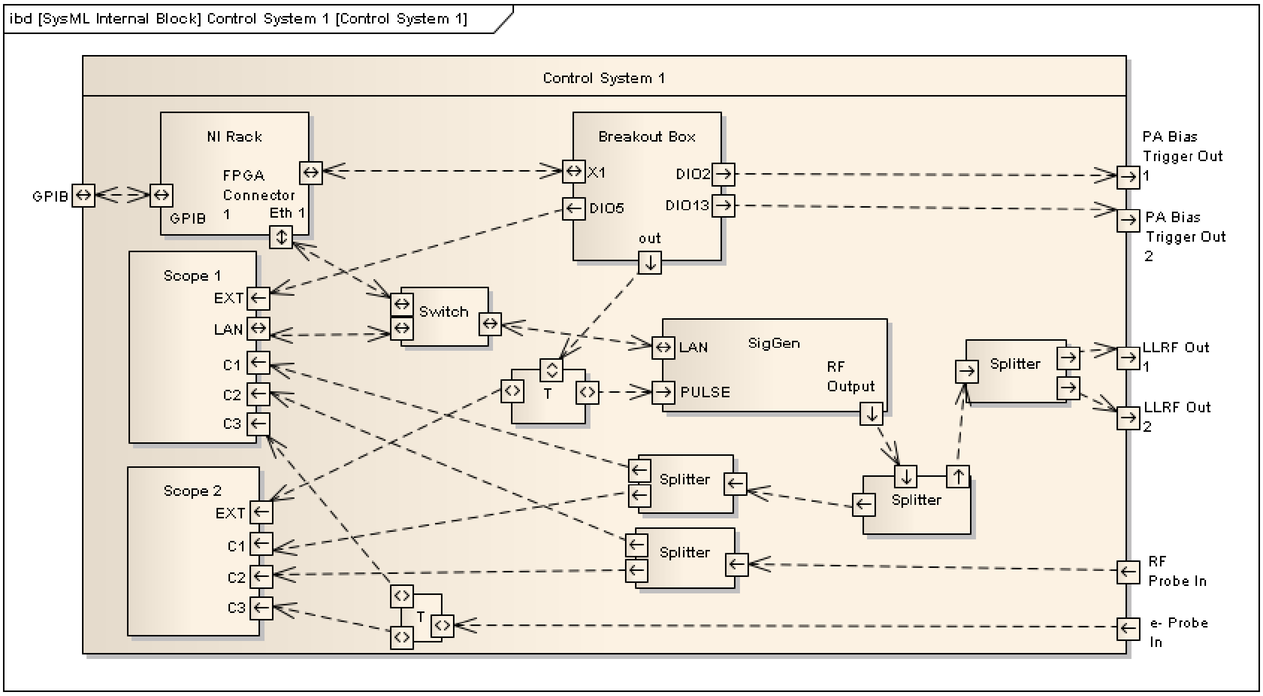

Figure 2: Analog Control System.

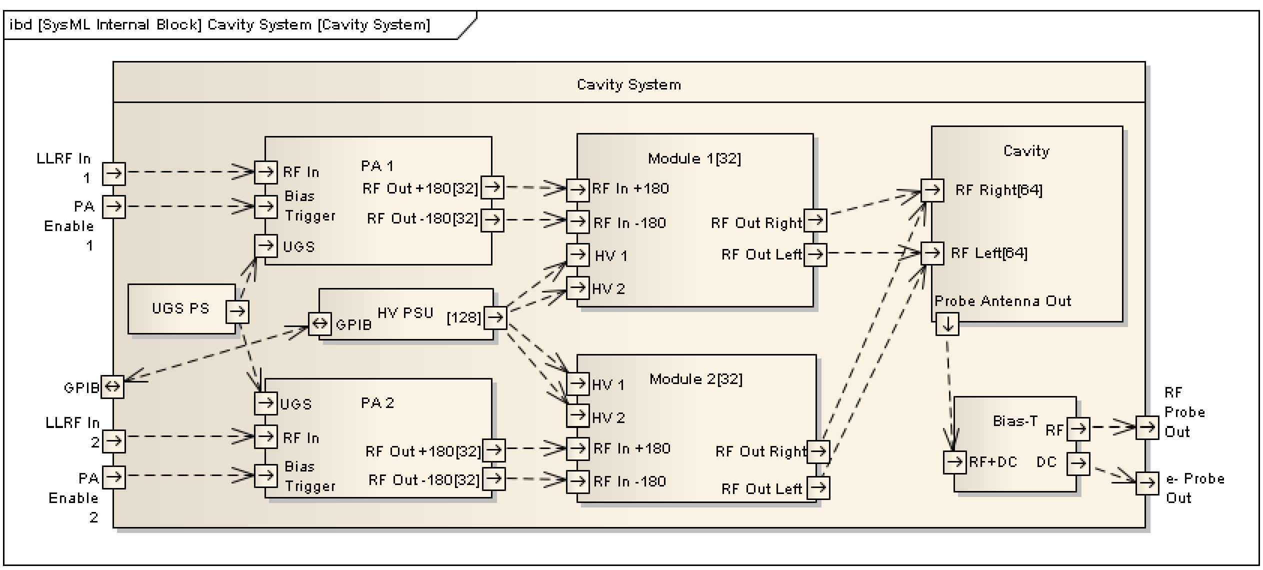

Figure 3: Cavity System (to control two groups of RF-modules).

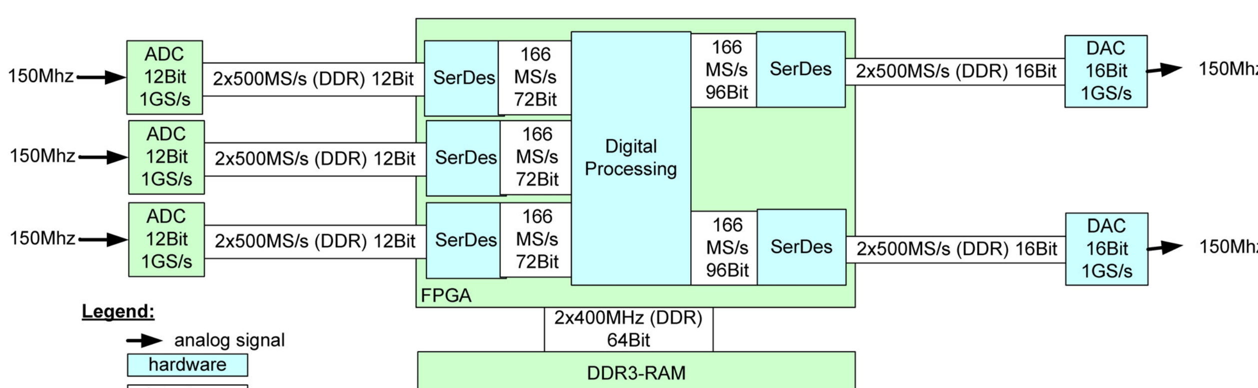

Figure 4: Data streams in the SCCRT.

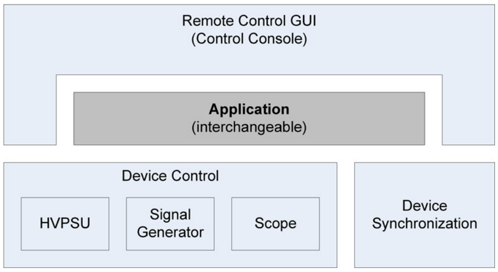

Figure 5: Control Software Concept.

Operating the directly driven cavity within the contect of an accelerator requires the ability to create an E-field with pre-defined and stable amplitude, frequency and phase during the whole particle injection phase of a macro-pulse. The analog control system used for the RF-module integration does neither have the control capabilities nor the timing accuracy required to achieve this.

The semiconductor driven RF-modules are non-linear time variant devices. In particular, the output power decreases over time due to discharging of the capacitor banks and self-heating effects of the SiC transistors during the pulse. The SiC RF-modules have their highest efficiency at maximum output power. In order to preserve the high RF-module efficiency while controlling the power fed into the cavity we are aiming at an outphasing control [7] like illustrated in Figure 6. Two groups of RF-Modules are driven separately with phases φ_1 and φ_2 and maximum output amplitude V_0. The cavity gap works like a combiner and inserts only the vector-summation V_{res} and φ_0 where

$$V_{res} = V_0 \cos\left(\frac{\varphi_1 - \varphi_2}{2}\right) \tag{1}$$

and

$$\varphi_0 = \frac{\varphi_1 + \varphi_2}{2}. \tag{2}$$

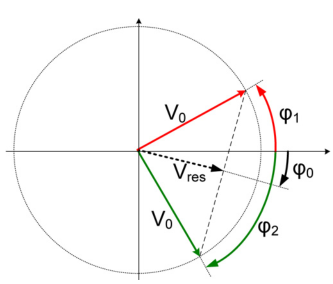

Figure 6: Outphasing Control Concept.

This requires that the control system can provide two LLRF signals that at least differ in their phases. We also would like to run measurements for detailed system identification. So we have to be able to acquire probe signals from the cavity and in the future also from the individual RF-module groups. We are expecting that these signals will have to be used in the future in order to realize a feedback control loop for increasing the accuracy of the cavity field. Therefore we decided to build a digital control system component called SCCRT (subsystem cavity controller real time) that gives us the required LLRF control and data acquisition capabilities and flexibility. The data streams in the SCCRT are illustrated in Figure 4. The core of the system is a Virtex 6 FPGA running at 166MHz. We have two RF output channels and three RF input channels for data acquisition. The 16 bit DACs and the 12 bit ADCs are running at 1GHz allowing the system to be used for RF frequencies up to 500MHz. The DDR RAM can be used for storing pre-defined RF-shapes and also for storing acquired RF and logging data.

The SCCRT furthermore can provide output trigger signals for synchronization of cavity system components. External events should be recorded and processed by the SCCRT as well, so the SCCRT also has input triggers. By handling all timing relevant issues within a single component we are aiming at maximum accuracy and minimum jitter. The SCCRT contains an internal 1GHz master clock.

The first revision of the SCCRT has recently been introduced in detail in [8].

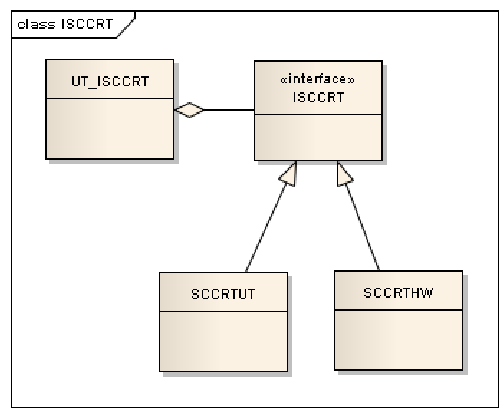

Figure 7: SCCRT Driver Class Diagram.

A LabVIEW [6] object oriented driver interface class (ISCCRT) has been used for defining the functionality and the programming interface for the first revision of the SCCRT, see Figure 7. The first driver client implemented is the class UT_SCCRT that provides a graphical user interface (GUI) for interactive tests of the driver. The class SCCRTHW provides the "real" driver communicating with the hardware while the class SCCRTUT is an implementation intended for validating that the unit test GUI is working correctly. Like intended, the use of the interface class allowed us to separate and parallelize the development of the software components. So the test GUI was available when the first hardware samples have been ready.

The next stage of experiments will start with the integration of the SCCRT into the control system replacing significant parts of the analog control system (see Figure 8).

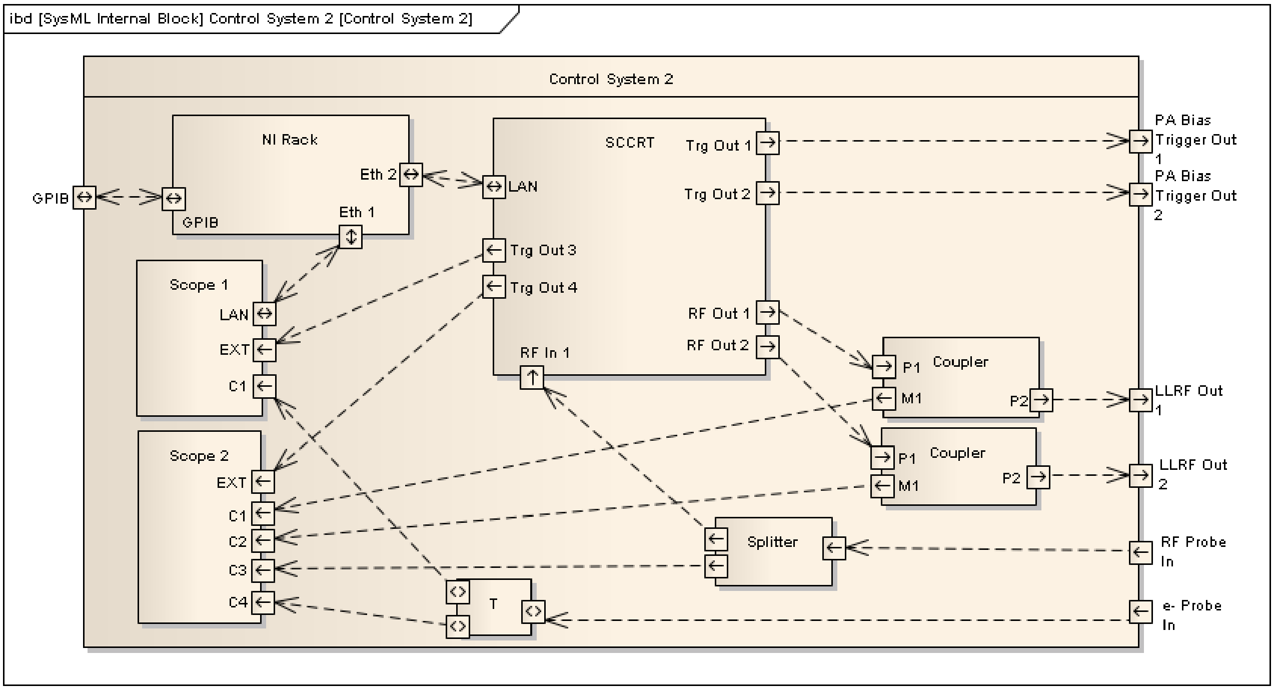

Figure 8: Digital Control System.

RESULTS

First commissioning tests with the 64 RF-modules have been carried out using the analog control system. At 150MHz and a RF-module supply voltage of 160V we have measured an E-field inside the cavity gap of approximately 66MV/m and a transmitted power of approximately 120kW.

The first revision of the SCCRT hardware has been assembled, the FPGA code is developed as well as the LabVIEW driver code. We have started the unit tests of the SCCRT.

NEXT STEPS

- Complete integration of the digital control system.
- The digital control system will be used for testing the outphasing amplitude control approach.
- The digital control system should be used for system identification purposes for gaining information for regulator design.
- The FPGA on the digital control system will be reprogrammed in order to support a closed loop operation with a PI regulator.
- Power injection tests with higher RF-module supply voltages should take us to the electrical field breakdown limits.

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