

Integration of the Digital RF System with the TTF Control System

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Introduction

The acceleration system at the TESLA Test Facility (TTF) Linac [1] consists of 64 superconducting cavities operating in pulsed mode at accelerating gradients up to 25 MV/m . Each group of 8 cavities is mounted in a separate cryomodule. Presently one cryomodule is installed in the TTF Linac. One common klystron drives 8 cavities and there are plans to supply power to 32 cavities in 4 cryomodules by a single klystron. The RF system supplies the 200 kW power to each cavity at an electron beam current of 8 mA. The control system must provide 0.1% of accelerating field stability for amplitude and 0.5 % for the phase. The major perturbation factors for the field are Lorentz force detuning, beamloading and microphonics. This is taken into account by the design of the RF control system. Another issue is the control of the vector sum of the accelerating field of up to 32 cavities connected to the single klystron.

1. Design of the TTF RF control system

The RF control system provides control of the vector sum and cavity tuning. It uses the accelerator timing events for the synchronization of the feedback and ADCs for diagnostics. Knob-box device for the operators convenience is also available.

1.1. Low Level RF Controls

The digital feedback system for the vector sum control has been developed with the goal of flexibility in different control algorithms (fig.1). This allows to measure and calibrate the accelerating field vector sum with high precision and invoke exception handling.

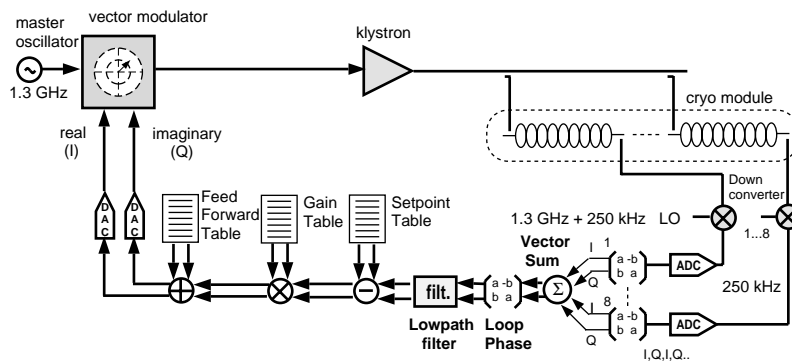


Figure 1: Digital feedback system scheme.

The digital feedback controls in-phase and quadrature component of the cavity field [2]. High frequency probe signals are used to measure the accelerating field in the individual cavities. These 1300 MHz signals are converted to 250 kHz and sampled by the ADCs with 1 MHz rate, i.e. two subsequent data points describe I and Q component of the cavity field.

The samples are scaled and rotated to compensate the delay in the cable length and calibrate the fields in the individual cavities. Then the sum of individual field vectors is calculated and rotated to adjust the loop phase. The vector sum is filtered by the low path filter and the feedback algorithm applies the proportional gain to the regulating error values (table). A feedforward table is added to the value of the calculated control action. The real and imaginary part of the calculated table are converted by the DACs separately and control the RF vector, applying the correction signal to the vector modulator.

1.2. Real time feedback design

The design of the low level control system to regulate the vector sum of the multiple cavities is based on the commercially available Digital Signal Processor (DSP) carrier board DBV44 from Loughborough Sound Images (LSI) with a Texas Instruments' floating point parallel TMS320C40 DSPs (fig. 2).

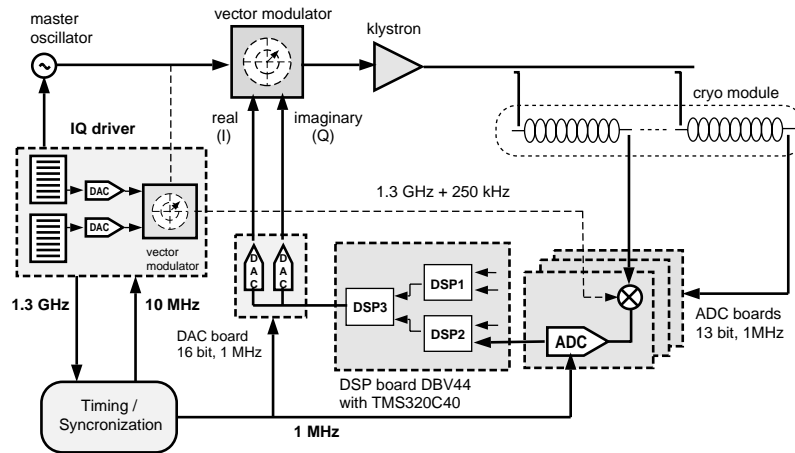


Figure 2: Real time feedback design.

The hardware of the digital feedback consists of 14-bit ADCs (Datel ADS 929) operated at a sampling rate of 1 MHz, the interface circuit to the input of the digital signal processors (DSP), the 3 DSPs (TMS320C40), and two 16-bit, 30 MHz DACs which drive the vector modulator. Two DSPs are used to acquire the probe signals of the 8 cavities and perform the vector rotation while one DSP is calculating the vector sum and performing the feedback algorithm. An additional DSP might be required to perform a more complex algorithm. The overall data processing time including ADC and DAC conversion is 3-4 us. The universal two channel functional generator with VME interface, called IQ driver, produces the local oscillator (LO) signal generated from the 1.3 GHz. It generates a 250 kHz bipolar step signal with ± 5 V amplitude to switch the LO phase in 90 degree increments.

1.3. DSP code

The present feedback algorithm is implemented in three DSPs on the DBV44 VME board. The interrupt service routines are used in all DSPs to start the data reading from the communication ports. The parameters of the feedback algorithm are modified by the DSP programs in a pause between beam macro pulses. It allows safely change the parameters of the control algorithm, apply the DC offsets for the feedforward table and vary the length of the pulse.

Due to time critical requirements all programmes were developed in 'C4x assembly language to minimize computational delay and increase performance. The internal DSP timer signal is used in all DSP to scale and rotate matrices in the case of the TTF timing system switches off. Two DSPs are used for the multiplication with rotation matrices and calculation of the vector sum of 8 cavity fields. The third DSP performs the filtering of the vector sum signal to reduce the sensor noise and calculates the control action in accordance with the used feedback algorithm.

All calculations must be done during a time shorter than the sampling period (1 us). For the 40MHz TMS320C40 modules it results in up to 40 instructions per 1us since multiplication and addition are performed in parallel. The correction of the DC offsets for the vector modulator is invoked by adding the offsets for the I and Q components of the feedforward table separately.

2. Implementation of DOOCS for the RF control

The Distributed Object Oriented Control System (DOOCS) from DESY is a control system (CS) tool which is used to solve a variety of control tasks in the TTF [3]. The DOOCS approach defines each hardware device as a separate object and this object is represented in a network by a device server, which handles all device functions. Such object oriented approach defined the choice of C++ as a programming language for the client and server parts of DOOCS libraries. Instances of devices and all properties of these devices are defined in the server program. All this definitions are transparent to the client programs and after the start of the device server all properties for that partial device are available to all clients in the network. This completely separates client programs from the device servers and modification of the server program has no influence on the clients because of symbolic access to the data.

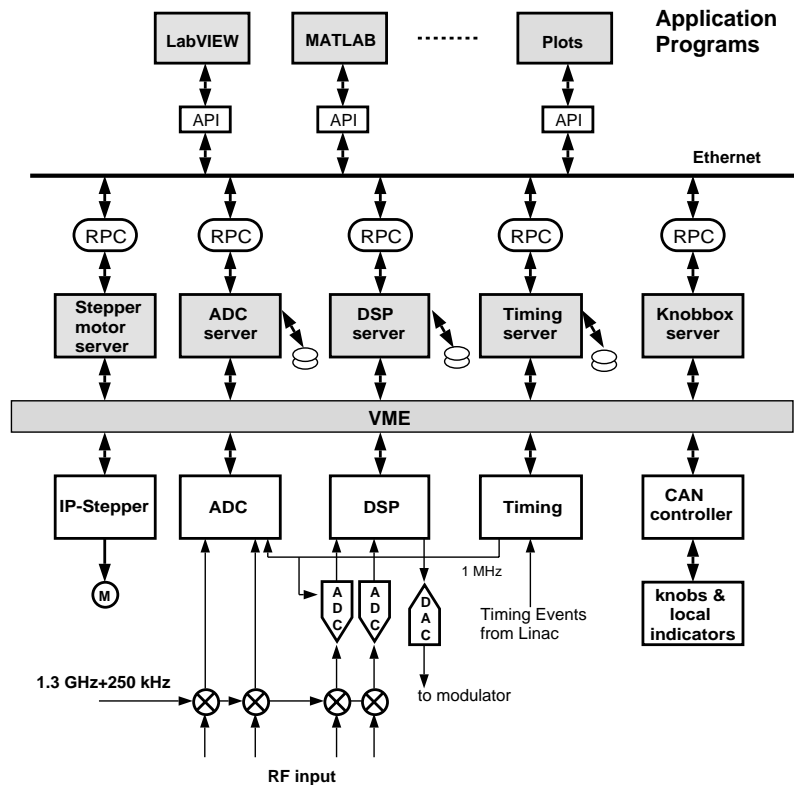


Figure 3: RF control system integration.

DOOCS supports multiple communication protocols and the feature to invoke new protocols. This allows to integrate the various accelerator subsystems with their own features and protocols and design a uniform control system for the whole accelerator based on a client-server model.

The real time low level RF control system described above is one of the accelerator subsystems. It is naturally integrated with the TTF control system, by development several DOOCS servers devoted to functionally self consistent part of it and the required client applications for the system management and diagnostic (fig. 3).

This set of servers includes the DSP server for the underlying real time feedback DSP-based control system and a server for Stepper motor controller. The ADC server for quick digitizers and timing server were developed for the operation in a number of TTF Linac systems and also are used by the RF control system. The control system for the cavities which are driven by a single klystron is considered as a functionally complete unit of the RF system.

2.1. DSP server

The DSP server controls the DSP board hardware and contains the required functionality for managing the real-time digital feedback subsystem. This DSP server hides the complexity of UNIX system programming and thereby simplifies client programming by the user of the control system. The functions executed by DSP server will make access to the low level RF system resources easy and transparent. The use of DSP server makes the CS flexible to allow for changes in the underlying low level RF system configuration. If the type, number of TMS320C4x modules, connection between TIMs or connection of the DSPs input/output signals are changed, it will require the changes only in the DSP server part of the CS. Furthermore significant part of such changes could be done just by customization of required settings in the server configuration file. CS designers can use symbolic addresses of the DSP data in their client applications to access the low level RF control system data.

The DSP server was designed based on DOOCS approach. It receives requests from the client application programs, does required actions and sends the reply to the client. A reply consists of the requested device (DSP) data and error state of the last server operation. The error part of the reply is the error code represented by an integer value and error string which explains the reason of last occurred error.

The DSP server provides for the client applications the set of functions which allows to use DSPs residing on DBV44 board in consistency with the CS configuration. This set of functions are defined in the DSP server and are accessible to the client as a set of PROPERTIES of the DSP board and RF system defined by the facility, device and location parts of DOOCS address.

The functionality of the server gives the user the opportunity to down/upload data into the DSP (feedback algorithm parameters) and download and start DSP code in each TMS320C40 processor on the DBV44 VME board. On top of these basic DSP server functions a set of objects for additional RF control system functions is available. This extended functionality provides access to the specific RF control system resources without announcing the details of the underlying system configuration. The problem of addressing the partial memory location in a separate DSP in the system are managed by the server internally and so are hidden from the client.

The DSP server maintains the cavity field gradient settings, exploring the number of parameters defined in terms of amplitudes and phases of the RF system data. It calculates and adjusts the set of the feedback algorithm parameters in accordance with the required field gradient value.

Another important feature of the DSP server is the possibility to execute a set of server functions during the single DOOCS request. This set of server functions are the number of

DOOCS requests, which are accessible to the client applications in the network, but they are not sent to the server over the network one by one. Instead they are prepared in a special command file or can be downloaded into server by the a client application remotely. Then the server can sequentially develop them upon receiving a special DOOCS request for execution. It is used to configure the low level RF control system, load the required DSP data and code and start the execution of DSP programmes in a right sequense at start time of the control system. It can be also used when the consistent set of the parameters of the RF control system should be changed at once on-line.

2.2. Stepper motor controller server

A phaseshift of the incident wave and loaded Q-factor of each cavity can be adjusted by the three-stub waveguide tuner. The movement of the stubs is managed by means of the stepper motors. Each motor is controlled by an IP module (IP-Stepper) residing on GreenSpring's VME carrier-board via the Superior Electric's motor drive — 440-EPI. This hardware has allowed us to achieve the positioning of stubs with step of 2.5 micron. The management of the tuner is carried out by the DOOCS stepper motor server.

2.3. ADC server

The ADC server emulates a digital scope for 4 channels. In an additional mode one or more channels can be used as a phase and amplitude detector for a RF signal converted down to 250 kHz. In case of TTF a frequency of 1.3 GHz + 250 kHz is used to the input of a downconverter.

One ADC has 4 channels of 12 bit converters with an integrated sample and hold unit. The sample and hold receives a signal from an external 1 MHz clock. All 4 channels are sampled at the same rate and at the same time i.e. the data in all channels are correlated. The data acquisition is started by an external trigger. This trigger is controlled by the TTF timing system. The number of samples to take is programmable in the ADC server. Typically 2048 samples are taken with a separation of 1 us and with a repetition rate of 10 Hz. This corresponds to 2 ms of data reading every 100 ms. Each channel is equipped with 64k words of memory. This memory wraps when it is filled. Therefore, the last 32 triggers may be stored in the ADC memory (assuming 2048 samples per trigger).

The ADC server combines two operation modes: a digital scope mode and a phase and amplitude detection mode. In the digital scope mode the current, e.g. the last taken samples, as well as old samples from the buffer memory of the ADC can be read. With the trigger rate of the ADC, typically 10 Hz, a programable point of the last samples is stored in a long time archiver. This is the standard archiver of the system. It stores the values together with a timestamp in a ring buffer. Storage is controlled by a filter setting. Long time drifts can be measured in this mode, for instance. There is a provision to store the last samples in an archive too. Read-back is done in the same way as the current reading. In an additional argument to the server the time stamp of the archived samples are specified. In the phase and amplitude mode all the mentioned functions are available too and in addition the samples are interpreted as phase and amplitude information also. Again buffers can be requested to give the most recent 2048-1 values of phase or amplitude. The long time archiver is also implemented. One point in phase and one of amplitude may be stored in the archiver with the 10 Hz trigger rate. Both values are calculated from two consecutive 1 MHz samples.

2.4. Timing server

Timing events from TTF Linac are used to synchronize all accelerator subsystems and are managed by the Timing server. Programmable timers are triggered by these events to generate the start pulses for the klystrons, DSPs or ADCs. A timer unit provides several independent output channels. Some machine parameters that change from macro pulse to macro pulse need to be delivered in time to run all digital feedback loops in parallel. The data words from the telegrams are stored in a dual port memory. This information is readable from the local connected computers.

3. Application Software

A set of generic and specially devoted programs provide the tools for the operators to control the RF system. Some of them were created based on the commercial products (LabVIEW, MATLAB/SIMULINK), others are in-house developed DOOCS client applications. However all of them use the DOOCS API to access the data.

3.1. LabVIEW tools for experts and operators

LabVIEW from National Instruments is used in RF control system and provides the user interface to the low level real-time digital DSP-based system, which performs the feedback algorithm. A Virtual Instrument (VI) library was created to access device data from DOOCS servers [4]. The LabVIEW applications start the initialization procedure for the digital feedback subsystem, by the execution of the command file for the DSP server, control the required parameter for field gradient settings, adjust the amplitudes and phases for the feedback algorithm parameters. The LabVIEW tool for generating various kinds of tables, required by the feedback algorithm is also available. Using the LabVIEW VIs is reliable and convenient in such system because the interface and layout of the system require significant additions and changes during the system evolution.

3.2. MATLAB/SIMULINK tools for RF system

The Application programs in MATLAB environment can access DOOCS servers by mean of the MATLAB external functions using the MATLAB Application Program Interface. These functions make the conversion of all numerical DOOCS data types to the appropriate data types in MATLAB environment and the other way round. Thus MATLAB's external functions using the device address as the argument carry out the data exchange with DOOCS server.

3.3. Identification of the system parameters and FF optimization

In addition to the feed back control loop which suppresses stochastic errors, feedforward is applied to reduce repetitive perturbations of the accelerating fields induced by beam loading and dynamic Lorentz force detuning. In the case of TESLA repetitive errors are dominating. The adaptive feedforward algorithm first identifies the time varying state space model of the closed loop system by measurement of a step response. Next the pulse to pulse average of the measured perturbations is applied to the inverse state space model to obtain the correct feedforward table. The goal of the adaptive feedforward is to determine the optimum feedforward table which minimizes the residual amplitude and phase error. The feed forward tables can be updated continuously to follow slow changes in the perturbation parameters. On-line system identification is transparent to routine beam operation due to the small step size used. Presently

the adaptive feedforward computer program is written in the Matlab programming language. Via DOOCS the program can read data from and transfer data to the digital signal processors. In the final version the adaptive feedforward computer program will be written in C++ language in order to integrate the program into the DOOCS architecture.

3.4. Knobbox invocation

The knobbox is a device with four independent knobs where each knob has a small four line display. One can program these displays with any ASCII text. This box is connected via CAN bus to a host computer. This computer runs a DOOCS server, which receives/transmits the events from the CAN bus. Through this server one can dynamically configure the knobbox to control every single value of the control system, e.g. the power of the magnets, drive stepper motors or in the RF system the gain and phase, by just turning knobs instead of using the computer mouse. The server sends with every knob event a configurable increment /decrement of the actual value to the device. The readback value is then written to the display at the knob. The advantage of such a knobbox device is, that one can concentrate on video-display or values on the screen, instead of searching mouse pointers.

Conclusion

The RF control system is running at TTF Linac more than one year and demonstrates the successful operation. Good reliability allows to explore the Linac and get the operational experience. Based on this experience the RF system is now under extension.

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