CONTROL SYSTEM FOR THE 1 MW NEUTRAL BEAM INJECTOR*

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Abstract

This paper presents general description of hardware and software of the neutral beam injector control system. The system is developed for control of the neutral beam injector which operates with 15-25 keV deuterium and hydrogen beams of 2 s maximum duration. It performs injection parameters calculation according to the desired beam power vs time curve, synchronizes and protects the injector subsystems and acquires its data during the shot. It also controls the injector operation between the shots.

The system is based on an industrial computer with National Instruments PCIe boards: two PCIe-7842R reconfigurable input-output modules and a PCIe-6323 data acquisition module. An in-house developed interfacing module (cross-box) as well as serial to fiber optic converters are used for galvanic isolation and electrical compatibility with the injector subsystems. User interface software and PCIe boards programmable logic firmware are implemented in LabVIEW. Injection calculations and results acquired are represented with MATLAB.

INTRODUCTION

An 1 MW neutral beam injector has been designed and built by the Budker Institute of Nuclear Physics (Novosibirsk, Russia) for the TCV tokamak of the Swiss Plasma Center (Lausanne, Switzerland) [1]. The injector parameters are shown in the Table 1. It operates in the pulsed mode and is aimed to produce deuterium and hydrogen neutral beams with an ability of the beam on/off modulation with millisecond resolution and of gradually varying the power injected into tokamak.

Table 1: Neutral Beam Injector Parameters

Parameter	Value
Max power injected in tokamak	1 MW
Beam power range	30 – 100 %
Beam power stability	± 5 %
Beam energy range	15 – 25 keV
Max injection pulse duration	2 sec.
Time delay between consecutive pulses	5 – 30 min.

The injector consists of an ion source connected to a vacuum tank where the gas neutralizer, bending magnet, residual ion dumps and moving calorimeter are mounted. The injector subsystems are located in two areas: gas system, ignition system, vacuum system, thermocouple modules of movable calorimeter and ion dumps and some parts of the RF supply are mounted near the injector in the tokamak zone. The rest parts including high-voltage supply system, power supplies for the ion source grids and bending magnet, RF supply electronics as well as control system equipment are located in the electronics zone being 50 meters away.

CONTROL SYSTEM

The system to control the injector was decided to be based on an industrial computer with a set of embeddable input-output modules. As injector operates in pulsed mode all its subsystems must be synchronized carefully during the injection pulse (shot). Also care should be taken of monitoring the subsystems status between the shots. Total number of channels required to control the injector operation is as follows:

- 24 analog input channels with the rate of 5 kSamp/s for monitoring the subsystems operation during the shot;
- 8 analog output channels with 10 kSamp/s rate to control subsystems parameters during the shot;
- 16 digital output channels with the maximum rate of 10 kSamp/s used for subsystems synchronization during the shot;
- 16 digital input channels with 10 kSamp/s maximum rate used as interlocks during the shot and between the shots as well;
- up to 40 digital input/output channels with the rate of less than 1 Samp/s to control and monitor the injector subsystems between the shots.

Since the control system equipment is distanced from the injector itself and partly from its subsystems, it was decided to isolate the system galvanically and connect with distant injector elements using optical lines and communication interfaces to avoid interference and crosstalks from injector and tokamak operation.

Hardware

Shown on the Fig. 1 is the injector control system block diagram. A SuperLogics industrial computer SL-3U-H77EB-GK with Windows 7 OS is chosen to run the control system software. It uses three PCI Express data acquisition modules by National Instruments as peripherals. Two of them are PCIe-7842R [2]: these reconfigurable input-output modules are based on a user-programmable Virtex-5 FPGA. Each module also has 16-bit resolution analog outputs with independent rate of up to 1 MSamp/s and analog inputs up to 200 kSamp/s. Another module used is PCIe-6323 data acquisition device [3] with 32 analog inputs of 16-bit resolution and 250 kSamp/s rate. Synchronization between PCIe modules is implemented by means of RTSI bus.

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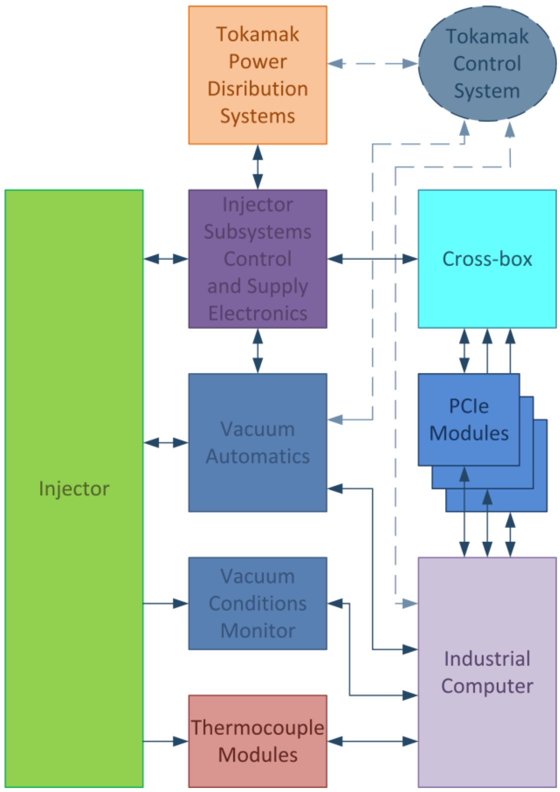

Figure 1: Control system block diagram.

All modules are connected to the interfacing device (cross-box) which is responsible for galvanic isolation and electrical compatibility between the control system equipment and the injector elements. The cross-box was in-house designed, its parameters are listed in Table 2.

Table 2: Cross-box Parameters

Parameter		Value
Analog channels		
Number of channels, input/output		24/8
Input and output voltage range		0 – 10 V
Input and output voltage accuracy		1 %
Channels bandwidth		50 kHz
Isolation voltage		1.5 kV
Digital channels		
Number of channels, input/output		
	electrical	16/16
	optical	32/32
Channels bandwidth		80 kHz
Isolation voltage		5 kV

The cross-box converts timing and interlock signals to/from optics. Also several signals of distant injector subsystems are transmitted via optical lines while electrical digital channels as well as analog input and output channels are used for communication with subsystems in electronics zone. The system analog outputs are used to control such injector parameters as ion source high-voltage supply values, RF system output power range, bending magnet current settings and others. For monitoring the analog subsystems parameters such as power supplies characteristics and beam position monitors data analog channels are used.

Another way of connecting the injector zone elements to the control system is via serial communication interfaces. The data is also transmitted with fiber optics to minimize losses and crosstalks and provide galvanic isolation and is converted to RS-232/RS-485 physical layers at the ends. Four serial channels applied are connected to the control system industrial computer as virtual COM ports. These channels are used for acquiring the injector thermocouple modules measurements, monitoring vacuum conditions and communication with the liquid nitrogen refilling system [4].

Software

The system software and firmware for the reconfigurable PCIe modules is designed in LabVIEW. The software is intended to perform several tasks as listed:

- analog control signals shapes and values calculation;
- timing signals synchronization sequences calculation;
- uploading sequences calculated into reconfigurable modules, checking its consistency;
- injector subsystems monitoring and control between shots;
- data acquisition and collection during and between shots;
- communication with the tokamak control system and its database.

The latter task features description is not an aim of this paper.

Control signals as well as estimated beam energy and ions and neutrals current calculation is performed with help of the MATLAB software using the MATLAB script nodes in LabVIEW based on the user defined power vs time curve. All data calculated and acquired during the shot (from data acquisition device and reconfigurable module internal memory as well) is then saved in a global structure along with shot parameters and settings to log the history.

The control system user interface with injector mimic panel opened is shown on Fig. 2. Different pages of the interface tab are displaying the injector subsystems information: moving calorimeter and ion dumps temperature measurements, vacuum conditions, interlocks and timers status and settings, power supplies characteristics and others. Each shot graphical results, including neutral beam power, energy, current vs time curves and subsystems parameters are displayed with MATLAB plots.

Firmware

System firmware is implemented in reconfigurable PCIe modules FPGAs to perform real-time operations during the shot. Four main tasks are of its responsibility:

- synchronization sequences generation;
- generation of analog control waveforms;
- monitoring of interlocks;
- acquisition of analog subsystems parameters.

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As control signals and synchronization sequences calculated are uploaded to the FPGA internal memory and its consistency is checked by the system software, FPGA state machine is set ready for the injection shot. When injection is initiated all timers and DACs outputs are started to update according to the waveforms data loaded. Also interlocks inputs are monitoring during the shot. Should any interlock signal occur, synchronization sequences generation will be stopped thus aborting the shot process.

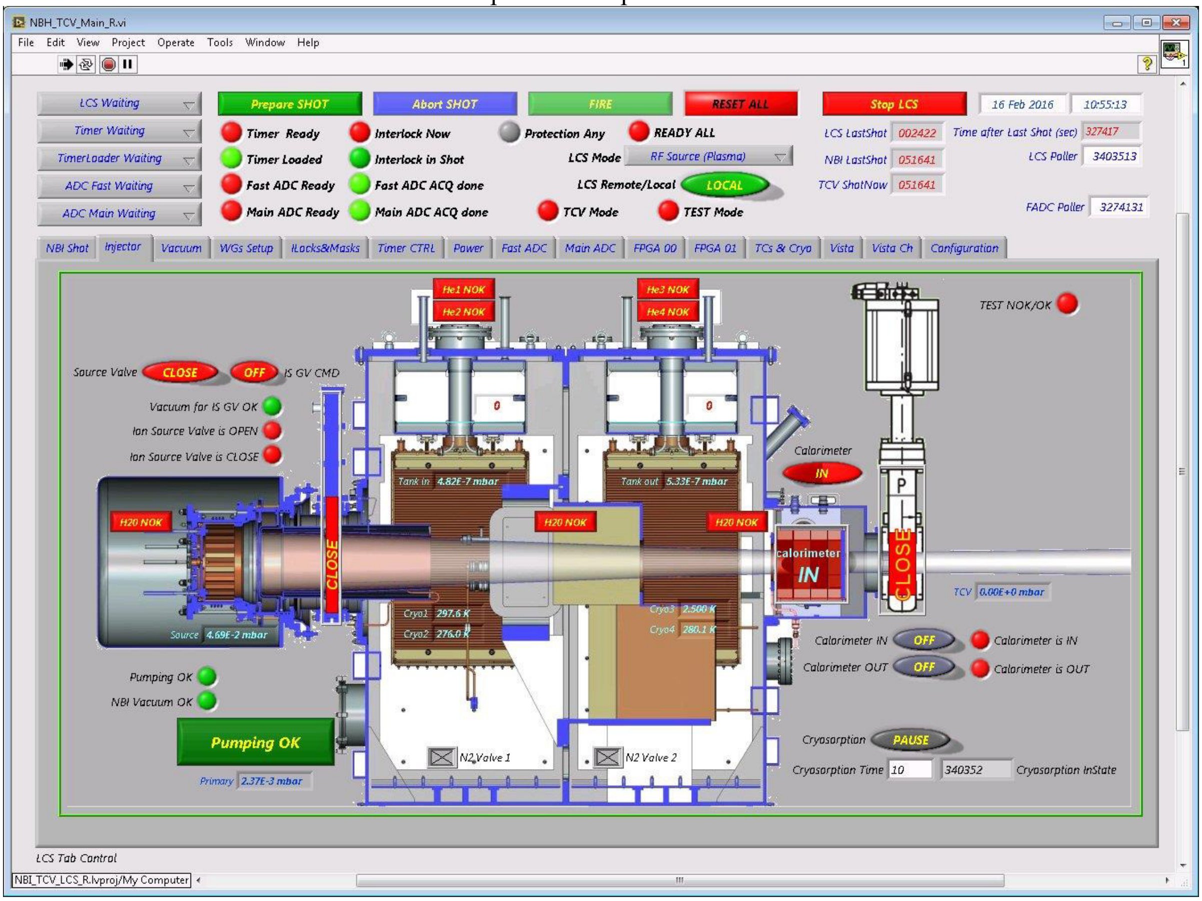

Figure 2: User interface.

COMMISSIONING

The system presented was commissioned during the injector assembling and tests performed at the Swiss Plasma Center in July-August and November-December 2015. In the late January 2016 the first neutral beam injector heated plasma was obtained at TCV tokamak.

REFERENCES

[1] TCV tokamak, `http:// spc.epfl.ch/research_TCV`

[2] NI PCIe-7842R, `http://sine.ni.com/nips/cds/view/p/lang/en/nid/207369`

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