NSLS-II BOOSTER INTERLOCK SYSTEM

R. Kadyrov#, P. Cheblakov, A. Derbenev, S. Karnaev, V. Mamkin, BINP, Russia
H. Hseuh, S. Buda, BNL, USA

Abstract

The NSLS-II injector synchrotron (booster) is a full energy injector for the 3GeV NSLS-II main ring being commissioned in BNL, USA. Together with Linac and transport lines it constitutes the NSLS-II injector [1]. Being responsible for its design and manufacture, Budker Institute of Nuclear Physics (BINP) also designs the booster control [2] and diagnostic systems [3]. Among others, the systems include an interlock system consisting of an equipment protection system (EPS), a vacuum level and vacuum chamber temperature monitoring and control systems, and a beam diagnostic service system. These subsystems are to protect facility elements in case of vacuum leakage or chamber overheating and to provide subsidiary functions for beam diagnostics. Providing beam interlocks, it processes more than 150 signals from thermocouples, cold cathode vacuum gauges and ion pump controllers.

Subsystems contain nine 5U 19" chassis with hardware of each based on Allen-Bradley CompactLogix Programmable Logic Controller. All the interlock-related connections are made with dry contacts, whereas system status and control is available through EPICS channel access. All operator screens are developed with Control System Studio toolset. This paper describes the functional design, configuration, operation and current status of interlock system developed and applied for NSLS-II booster.

INTRODUCTION

As any other research facility, the NSLS-II accelerator complex can produce a number of hazards both for equipment and personnel. A set of systems of different operation control area was developed to eliminate and control these hazard sources: a separate interlock system controls Linac hazard, the other covers injection transport line, booster ring (BR) and extraction transport line. The main storage ring (SR) has its own protection system. The systems have own control area with a variety of hardware and software interconnection points between them.

Personnel protection system (PPS) processes all injector interlocks and provides protection for people engaged in machine maintenance. PPS mainly provides facility access control during operation and is not described in this paper. BR and transport lines interlock system is within the scope of this paper. Booster interlock system includes several subsystems: temperature control, vacuum control, power supplies status control, and EPS.

r.a.kadyrov@inp.nsk.su

SYSTEM REQUIREMENTS

High facility safety requirements impose some strict principles of fault-tolerant interlock system design:

- All interlocks received should be hardware based. No software signal transmitting media can be trusted, so a source must be able to signal the interlock condition to the system even in case of main operation software stuck or failure. Network can be used only for status monitoring (e.g. for operator screen), not for subsystems interconnection. The system processes safety interlocks from different sources: subsystems and end equipment. Interlocks come as hardware signals of different type. For instance, temperature control processes signals coming from thermo relays as binary relay signals, whereas signals coming from thermocouples for continuous temperature readings are analog.
- Interlock signals processing should be made separately from main facility operation code execution. A separate logic device is needed to process data independently from main operation software, so a stuck or failure of the later should not prevent interlock logics from being properly executed, and the interlock system has to keep performing its operation.
- None of interlocks can be disregarded in any way but by hardware means. For example, the status signal from a faulty subsystem coming as a relay signal can be substituted by a wire loop on the connector or terminal. So a hardware change is to be done in order to continue normal operation, assuming a high level of access and deep understanding of interlock cause.

SUBSYSTEMS

A set of subsystems was developed: temperature and vacuum control subsystems, equipment protection system and others.

Temperature Control Subsystem

There is a 60°C normally closed thermo switch mounted at the cooling water output of each magnet cooling circuit in the booster ring. There are two daisy-chained switches on the each magnet of BD-type. Signals from switches are analysed by thermo switch control system (TSW). If a magnet is overheated, TSW informs EPS about it via the hardware signal. The EPS processes it and generates the output signal to the magnet power supply. The PS treats this signal as external interlock and initiates a shutdown procedure. TSW transmits thermo switch status into the network, so magnet thermo switch status can be seen from the operator panel.

ISBN 978-3-95450-139-7

BR consists of 4 arc sections and 4 straight segments. There is a hazard of arc overheating due to synchrotron radiation, so additional temperature control is made. The function of BR vacuum chamber temperature control resides in the vacuum control subsystem.

Vacuum Control System

Vacuum control system provides slow control for mechanics — vacuum gate valves (GV) that isolate adjacent segments of the chamber: arcs and straight sections. GV is normally closed and can be opened by energizing the flap solenoid for the compressed air. GV has ending switches so the subsystem can determine whether it is open or closed. GV can be opened or closed through the subsystem by remote command from network, including the command initiated by operator from the control screen. The subsystem closes GV automatically in case of vacuum fault.

The interlock system processes vacuum state status signals coming from various vacuum pump and gauge controllers. An average pressure below 10^{-7} Torr in BR is required for normal beam operation [1]. Vacuum measurement is presented by vacuum gauges and ion pump controllers (IPC). Thermoconductivity gauges (TCG) operate in low and medium level vacuum, cold cathode gauges (CCG) measures measure the pressure down to 10^{-11} Torr. There two CCG and one TCG mounted at the each arc and straight section of the BR. Gauges are controlled by MKS 937B vacuum gauge controller (VGC). VGC can control up to two CCG and two TCG sensors. It has a pre-defined set point and normally closed output relay signal for each sensor channel. If pressure measured is less than threshold set point, output relay signal is closed, and it is open in case of pressure rise. The current value for threshold vacuum level is $2*10^{-6}$ Torr.

The pressure of such level is maintained by Gamma Vacuum diode type ion pumps (IP) that are controlled by Agilent Technologies dual channel IPC. IPC provides means to monitor the vacuum level through the discharge current which is proportional to pressure level. IPC also has a pre-defined set point and normally closed relay signal for each channel. The current value for threshold vacuum level is $2*10^{-6}$ Torr. There are more than 70 IP maintaining the vacuum on the BR. The BR vacuum subsystem processes vacuum level status signals from IPC for IP mounted close to the gate valves.

The distinct criterion was developed to detect a vacuum fault in the arc or straight sections. The subsystem continuously monitors the vacuum status signals and generates interlocks if pressure rise was detected. It closes two adjacent GV to isolate section and ensure that the leakage doesn't spread the pressure rise further. Closed GVs cannot be opened until vacuum recovery as measured by IPC, CCG and TCG in corresponding section.

Vacuum control subsystem informs the EPS system about closing GV to protect it from being hit by beam, and indicates the current vacuum level at the section is inadmissibly low for accelerator equipment (e.g. kickers) operation.

There are up to 12 customised resistance temperature detectors (RTD) mounted on each arc and straight of the BR. The temperature readings from the system can be monitored through the network. Currently there is no overheating interlock generated on the base of RTD readings.

Equipment Protection System

The EPS conveys a function of general protection of equipment in case of accident or inappropriate configuration. It receives and processes hardware signals coming from different monitoring and interlock systems. EPS creates multiple output signals to Linac interlock system and power supplies. These signals are treated as external interlocks in remote systems. The system interfaces interconnection scheme is shown in Fig. 1.

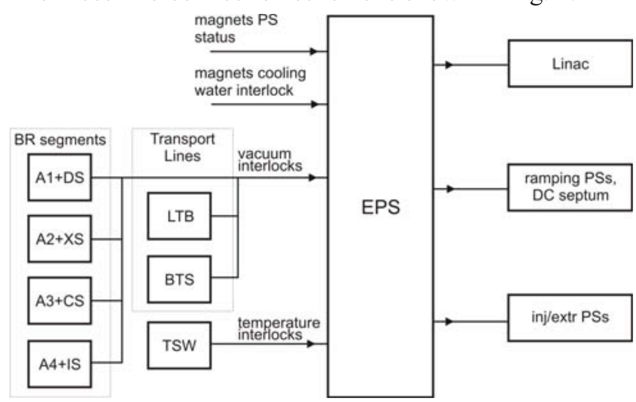

Figure 1: EPS subsystem interfaces.

Besides vacuum and temperature interlocks coming from subsystems described above, the system receives the interlock signal from the tunnel magnets cooling water system (DIW), transport line magnets power supply and extraction septum monitoring systems. The monitoring systems watch if magnet power supply is switched on and its parameters are compatible with the beam energy. Incoming signals type and voltage range are listed in the table 1.

Table 1: System Signals Type and Voltage Range

Origin	Signal	Type/Range
IPC	Pressure Recorder	Analogue, 0 – 5V
IPC	Threshold Set Point	Relay
GV	Solenoid	24V, 500mA
GV	Status: Open/Closed	Endings
VGC	Threshold Set Point	Relay
Subsystems	TSW, DIW, Vacuum	"Dry" contacts

The EPS main protection function is to enable Linac gun operation if an acceptable environment for beam passing through the injector is made: beam path isn't

ISBN 978-3-95450-139-7

block by any closed vacuum gate valve, vacuum is good enough, and bending magnets are on.

Different injector operation modes involve various combination of equipment to be checked to enable mode operation. For instance, if beam comes from Linac directly to one of the dumps on the transport lines, the system checks valve and magnet states in the transport line only and does not care about BR equipment state because the beam is dumped and does not reach the BR.

There are four possibilities to work with the beam:

- the beam doesn't leave the Linac tunnel and follows straight to one of the dumps;
- the beam is sent to the booster (injection and acceleration in BR);
- the beam is sent to the booster and being extracted to transport line follows toward the dump;
- the beam successfully passes through the whole injector and goes to the SR.

The EPS function is to enable Linac gun operation if an acceptable environment for beam passing through the operation area is made in corresponding to injector mode of operation.

The system also performs the kicker protection function: in case of inadmissibly low vacuum in operation section as it was measured by CCG and reported by vacuum control system.

The EPS interlocks BR magnets power supply if the magnet coil is overheated as it was reported by TSW or if cooling operation is in fault state as it was indicated by DIW.

INSTRUMENTATION BASE

The rigid system requirements described above imposed specific restrictions on the choice of the existing solutions for the organization of interlock subsystems. The similarity of the tasks of processing data and generation a number of interlocks for various subsystems makes reasonable the approach of developing a unified functional block structure. Each subsystem is represented by chassis-based system with separate internal logic controller. There is a number of suitable industrial solutions for logic operation within a subsystem: FPGAs, single board computers, programmable logic controllers (PLC).

The Allen-Bradley 1769 series Compact I/O modules and 1769-L32E logic controller were chosen for its availability, ease of use and programming. Ladder logic used for PLC programming is straight forward and doesn't require a deep knowledge of text-based programming languages, which makes issues easy to debug. Code maintenance and update can be approached without developer involvement at stages of facility commissioning and its further operation. Together with I/O modules, auxiliary elements, terminal blocks (TB) and internal wiring, each PLC resides in an enclosed cross-box chassis.

BR vacuum control system consists of 4 cross-box chassis. Each chassis controls one arc and the following straight section of the BR. Two identical chassis control injection and extraction transport lines. Single chassis performs TSW subsystem operation, the other chassis conveys EPS functions. The chassis are mounted in different racks closed to the equipment and subsystems controlled to make interconnection cables short and neat.

The internal structure of each chassis is based on Allen-Bradley industrial automation hardware elements: 1769-L32E PLC, 32-channel input modules 1769-IQ32T, 8-channel relay output module 1769-OW8I, 24V DC power supply 1769-PB2 for internal PLC bus, 24V DC 1606-XLS240E for chassis circuitry and auxiliary elements, terminal blocks and circuitry. Vacuum control chassis are equipped with 1769-IR6 RTD modules and Allen-Bradley PanelView 600 6'' touch screen mounted on the front panel of the chassis. It monitors vacuum system states in controlled injector area and let the operator to troubleshoot accidents on the spot. Heartbeat signal, power and network status are connected to the indicator LEDs on the front panel of the chassis.

The hardware and auxiliary terminal blocks are DIN-rail fastened together with binding electrical cables located in the 5U 19" anode metal chassis mounted in the rack. The system chassis internal layout is shown in Fig. 2.

Figure 2: Internal chassis layout.

Internal wiring and TB perform cross-box functions of signal crossing, their normalization, I/O module ports protection and signal decoupling. Modules I/O ports are protected by making use of fuses and suppressors included to internal circuitry and mounted on TBs. Each cable inside the chassis is labelled with its number and type, so connection can be found and troubleshot using reference diagram or full electric schematics.

To avoid any ground loops and ground sharing between different systems all digital connections among subsystems are made as isolated "dry" contacts (each signal is common terminal and normally-open relay contact pair). Binary status from equipment and subsystems are received as relay signals, closed while normal operation and open in case of interlock (alarm, accident), so interconnection cable break and loss of

ISBN 978-3-95450-139-7

connection cause interlock from misconnected source. All source inputs are low-voltage connections with current limited resistors, thereby preventing short-circuit and block failure in case of cable misconnection or break.

Engineering full electrical schematics of internal structure of each chassis was developed for system replication, repair and further hardware development. Detailed block-diagram of the wiring was also provided for quick reference and easy troubleshooting.

Unified internal structure of a chassis made possible to implement hardware means used in interlock subsystem and to develop a chassis with auxiliary beam diagnostics elements used in NSLS-II injector as well.

SOFTWARE

The PLC logic was implemented with Rockwell Automation RSLogix 5000 IDE. Its ladder-logics approach makes incoming signal processing easy and clear. Each ladder step performs one of the EPS protection scenaria: Linac gun interlock, PS and kickers protection etc. Operation logic and interlock states are fully described with flow charts and state diagrams in system description and user manual.

PLC received and transmitted status and interlocks are available as global tags for network access and inter-system communication. This data is available through Ethernet/IP protocol and can be gathered in EPICS used at NSLS-II facility with Ethernet/IP driver [4]. The driver is included to the EPICS software I/O controller (IOC) running on the separate IBM PC server assigned for interlock status acquisition and monitoring.

Interlock status monitoring

A set of engineering screens and operator monitor was developed using Control System Studio (CSS) toolset [5] to monitor interlock state.

The EPS input signals and output interlocks state is shown in the summarizing monitoring screen (Fig. 3). The panel on the left side of the screen shows interlock source data: each input binary signal colors the indicator in red if relay contact is open (accident case, interlock) or green if contact is closed (good operation, no interlock). Right side of the screen monitor shows interlocks developed by the EPS after processing input data: output binary signal colors the indicator in red if EPS opens the relay contact (accident case, interlock) or green if contact is closed by EPS (good operation, no interlock). Remote side (Linac PLC, kickers, PS) should treat this output signals as external interlocks. EPS logic assumes that there is at least one input interlock source active if an output interlock is generated. The screen makes troubleshooting easier and makes EPS operation logic visually clear.

TSW monitoring screen was also developed, its layout coincides with measurement equipment location in the injector tunnel, so the magnet with thermo switch installed and overheated can be easily found.

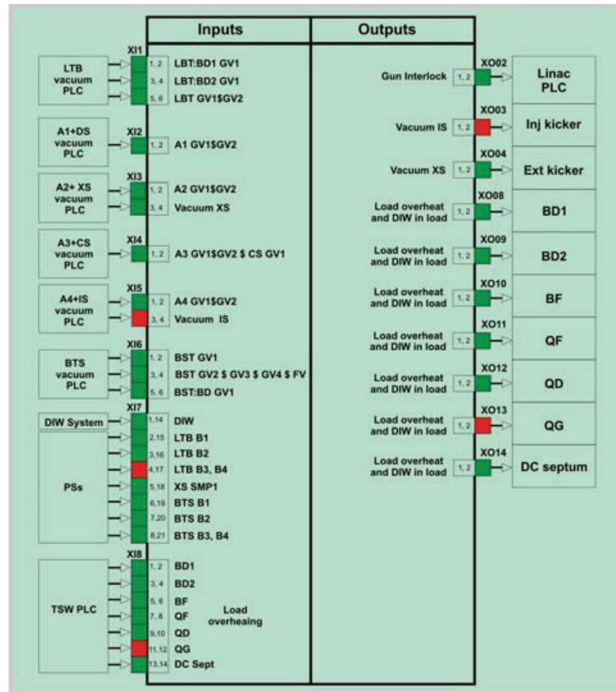

Figure 3: EPS monitoring screen.

Vacuum control screen was also developed. It receives data directly from controllers (VGC, IPC) and from each vacuum PLC chassis. It helps to monitor GV status and pressure rates at different injector sections. Operator sends remote commands to open or close a GV through this monitor.

SUMMARY

The interlock system of NSLS-II injector includes Vacuum control system, Temperature control, and Equipment protection system. Nine similar chassis based on Allen-Bradley 1769-L32E PLC logic, 1769 series Compact I/O were designed, assembled, programmed, installed and tested. PLC logic was implemented with RSLogix ladder diagrams, main status and interlocks being available through network and shown on the operator panels. The system is ready for the booster commissioning.

REFERENCES

[1] S. Gurov et al., “Status of NSLS-II Booster”, IPAC’13, Shanghai, May 2013, MOPEA053, p. 196 (2013); http://www.JACoW.org

[2] S. Karnaev et al., “Status of the NSLS-II Booster Control System”, MOPPC108, ICALEPCS 2013.

[3] G. M. Wang et al., "NSLS II Injector Integrated Testing", IPAC’13, Shanghai, May 2013, THPEA063, p.3285 (2013); http://www.JACoW.org.

[4] http://ics-web.sns.ornl.gov/kasemir/etherip/

[5] http://cs-studio.sourceforge.net/

ISBN 978-3-95450-139-7