Control System for Superconducting Electron Cyclotron Resonance Ion Source with Advanced Design in Lanzhou II

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Abstract. The newly built SECRAL II (Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou II) is a multi-purpose intense highly charged ion source and is of great significance at Institute of Modern Physics (IMP). The control system is an important subsystem of SECRAL II. In this paper, we implement a control system for SECRAL II. In order to achieve high quality control, we have presented and followed some useful control concepts. The control system can perform control and monitor of all devices. Besides, it can also complete data store, alarms, interlocks and human safety. In all, the control system effectively supports the operation for SECRAL II. The control system was completed and put into operation in June 2016. The control system has successfully worked for about 11000 hours. During this process, the hardware works normally and without trouble. The control software has a low failure rate (5.5×10⁻⁴/hour) and its MTTR (Mean Time to Repair) is less than 30 minutes. Since then, SECRAL II has set many world records in the field of ECR ion source.

1. Introduction
The newly built SECRAL II is a sophisticated facility involving varieties of devices. Its control system is an important part owing to the fact that the stability and reliability of operation of an accelerator much depend on its control system [1]. Control system for a superconductive ECR ion source is a great complex of both hardware and software, which involves so many technologies and variety of control requirements and must be taken into consideration carefully. In addition, taking into account that SECRAL II is built to keep in service for several tens of years, relevant requirements (reliability, stability, maintenance costs, etc.) [1] are rather demanding.

This paper mainly describes the design and implementation of control system for SECRAL II project and is structured as follows: SECRAL II infrastructure will be described briefly in Section 2. In Section 3, we explain implementation of control system in detail. Finally, conclusions and future work is in Section 4.

2. Facility overview
The SECRAL II Project is composed of a superconducting ECR ion source and a length of ionic beam transmission line. The SECRAL II facility is shown in Figure.1. SECRAL II is running at 28 and 18GHz [2]. By injecting microwave of proper power level and raw materials into vacuum chamber under appropriate magnetic field, the ions of plasma are generated. In order to extract ion beams from plasma, an electrical potential difference is necessary. The max extraction high voltage is 30kV. Therefore, the plasma chamber and some equipment needed to generate ion beams must be placed on a high-voltage platform (HVP) to enable effective extraction.
After plasma is generated, a series of measures have to be taken to achieve high quality ion beams. A solenoid located close to ECR of SECRAL II, adjusted by means of a power supply, was used for ion beams focusing. SECRAL II can produce multiple charge states for a given nuclide, whereas it only needs to provide a particular charge state at a certain moment. Therefore, after strong focusing, ion beams are delivered to a 90° double focusing bending magnet, which was utilized to select the ion beam of specific charge state of the given nuclide according to the final application. Following the bending magnet is a group of triplet used to enhance the optical resolution of ion beams. Next to the triplet is another solenoid used to do beam coupling de-correction compensation [2]. The last is some beam diagnostics such as beam slits, Faraday cup and vision sensor.

![SECRAL II facility](image)

**Figure 1.** SECRAL II facility

### 3. Control system implementation

#### 3.1. Philosophy of implementation in control system for SECRAL II

In order to implement a high quality control system (reliable, stable, extensible, maintainable, etc.), some general principles should be followed.

Firstly, in order to achieve good performance, we should design control system to be a loosely coupled architecture. This architecture guarantees the furthest reduction of the interdependence between hardware and software. Besides, this architecture is a necessity to mitigate the requirement of controlled devices specific and to lubricate the integration of hardware and software in the whole system. In all, this architecture can improve the reliability of the system largely.

Secondly, standard front-end hardware (individual controllers) according to its function (control, interlock, etc.) should be the preferred approach. The advantage is that standardized hardware often offers less bugs, longer lifetime and better interchangeability. This implies that we should select mature and frequently used hardware in industry automation. For example, PLC is suitable for slow control while PXI module is preferred in fast control and high-speed data acquisition [3].

Thirdly, we must develop software properly, which should provide a platform integrating all sorts of hardware and protocols together systematically and seamlessly. EPICS has been widely used in particle accelerators especially in those of large scale [1] and has a large user community. Besides, EPICS [4] is the software toolkit of control system used in HIAF project [5]. It is the new control software framework for HIRFL and CSR during their upgrade. The work discussed here chooses EPICS as the integrated development toolkit without exception.

#### 3.2. Control system architecture

Based on the idea mentioned in Section 3.1, the control system is designed and subdivided into three layers as designed and illustrated in Figure 2.
Figure 2. Architecture of control system for SECRAL II

The GUI layer is the graphically interactive operation interface for SECRAL II operators. The control and monitor layer is the core of whole control system. The control and monitor of all devices is finished in this layer. This layer provides a transparent communication environment to integrate all hardware devices, protocols and software components together. The communication mechanism between this layer and GUI layer is the EPICS Channel Access (CA) protocol. The front-end devices layers include all individual controllers. There are varieties of the communication interface of individual controllers. We used gateways to convert these serial protocols to TCP socket for data exchange through the control network. In the view of EPICS, there is only one kind of control interface, which is Ethernet. Thus, individual controllers integrate together into the control system network seamlessly. This makes control architecture more flexible and scalable.

3.3. Hardware setup

We used two powerful industry computers (IPC) from Advantech running CentOS 6.6 as EPICS Input/output Controller (IOC) with front-end control software running in them. One IOC integrates all hardware devices together through control network and communicates with the outside with process variables (PV). It also manages part of interlock, alarm and human safety. The other was dedicated to the control and monitor of superconducting magnet power supplies because these power supplies need to be monitored all the time even SECRAL II is not in operation.

We used another PC running Windows as GUI based on Control System Studio (CSS) [6].

In order to obtain high reliability, we employed a pair of redundant PLCs from Phoenix Contact. In order to enhance the stability and reliability of control system, all analog signals are isolated through optical couplers before output from or input into PLCs. This pair of redundant PLCs with scan time 2ms synchronized by an optical fiber to achieve the following tasks:

1. Integrating all internal hardware modules through PROFINET field bus and completing data exchange with IOC based on TCP socket. The PROFINET bus provides Isochronous Real-Time communication between master station and slave station with 1ms response time and 1μs jitter.
2. Providing analog control signals to analog-interfaced devices such as high-voltage PSs for beam extraction and suppressor.
3. Acquiring analog read-back signals from analog-interfaced devices.
4. Providing digital output signals to activate devices or trigger interlocks and alarms.
5. Acquiring digital input signals to obtain status of the devices.
6. Processing some logic calculations of interlocks and alarms.

Taking into consideration of interchangeability and maintenance costs, we selected servomotors of the same model from Parker Hannifin for motion control mentioned before. The drivers of these motors provide the outside with RS232 converted to TCP socket by gateways finally. The hardware setup is in Figure 3.
Figure 3. Hardware installation of control system for SECRAL II

3.4. Software and integration
Based on the control concepts mentioned in Section 3.1, software and system integration becomes more straightforward and is as follows:

(1) IOC controls two of three power suppliers on the high-voltage platform (HVP) through control network. The operators tune bias power supply (PS) through a remote PID module with Ethernet-interface. By sending commands and receiving state values, we can control the bias PS remotely.

(2) According to their control protocol, IOC controls devices such as magnet power supplies, multi-meters and vacuum gauges through sending commands and receiving state values through TCP socket.

(3) The pair of redundant PLCs communicates with its I/O modules via PROFINET and provides the outside with TCP socket. So, IOC need only exchange data with PLC via TCP socket while need not care about the I/O modules of the PLCs. Borrowed from the EPICS driver "S7plc" for Siemens S7 PLCs [7], the so-called “send/receive” protocol is adopted as well to accomplish communication between IOC and PLCs. Details of this communication mechanism are in [8].

(5) As for data storage, we developed a new data archiver based on C# and Python. The data archiver collects and save data to excel files. Besides, we developed a new log system for recording the interlock and alarm information in database. In order to facilitate operators, we developed a network document system based on web technology.

3.5. Alarm and interlock mechanism
During the operation of SECRAL II, malfunction or undesirable operation state can hardly be avoided which may be harmful to controlled devices. In this context, we implemented alarm and interlock mechanism to ensure good operational performance.

We use alarm mechanism to notice operators that status of the facility is abnormal. If the situation is going worse, the interlock mechanism will take effect to shutdown relevant devices.

Each device (trigger source) has two level thresholds that are stored in database and can be re-configured. The first level threshold values are related to alarms while the second level threshold
values correspond to interlock. The threshold values use “OR” logic. This implies that any trigger source can trigger alarms and interlocks.

Both IOC and redundant PLCs are both take part in the implemented alarm and interlock mechanism. IOC fetches the level thresholds from database. For some trigger sources, IOC obtains their current values through its control interface. Then, the comparison operation is in IOC and result is sent to redundant PLCs, which will finish all logical calculations and then execute actions of alarm and interlock mechanism. In this sense, the response time is about 100~200ms. With regard to devices of analog or digital control signals, redundant PLCs obtain their current state values directly. IOC obtains their threshold values from database and sends them to redundant PLCs. Thus, the comparison operation and logical calculations are both in redundant PLCs. Under this context, the response time is about 2ms. All information of alarm and interlock recorded is in IOC, stored in database and displayed in GUI and log system.

3.6. Human safety
SECRL II was located in a clean hall surround with an iron fence. When SECRAL II is in operation, humans must not enter the hall. High voltage as well as microwave and ion beam radiation hazards must be avoidable. The clean hall includes two doors with a key signal individually. The key signals gathered is in the redundant PLCs, which are in charge of the logical process of human safety. If the any door is open, both the microwave machine and the high voltage PS are cut-off. An alarm lamp controlled by the redundant PLCs with five lights of different colors and a buzzer are also employed to alert operators and inform them the status of SECRAL II.

4. Summary and future work
In order to build a control system of good quality, we have proposed and followed control philosophy. The control philosophy applies to particle accelerator field and may find its place in general industrial control field. With respect to SECRAL II, based on the loosely coupled structure and EPICS, we implemented the control system finally.

Since its completion in June 2016, the control system has successfully worked for about 11000 hours and supported operation of SECRAL II. During this process, the hardware works normally and without trouble. The control software has a low failure rate (5.5×10^{-4}/hour) and its MTTR (Mean Time to Repair) is less than 30 minutes. Since then, SECRAL II has set many world records in the field of ECR ion source for beam intensity, such as \( {^{16}\text{O}}^{6+}(6700\text{eμA}), {^{16}\text{O}}^{7+}(1750\text{eμA}), {^{40}\text{Ar}}^{12+}(1190\text{eμA}), {^{40}\text{Ar}}^{17+}(120\text{eμA}), \) etc.

Currently, SECRAL II runs in CW mode. In the future, it may work in afterglow mode [9]. This implies that we should adopt and incorporate some other devices for fast control and data acquisition. Based on the loosely coupled structure and EPICS, this will be favorable and smooth.

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