Development of Hard-wired Instrumentation and Control for the Neutral Beam Test Facility at KAERI

Ki-Sok Jung†, Byung-Joo Yoon*, Jae-Sung Yoon* and Min-Seok Seo*

Abstract - Since the start of the KSTAR (Korea Superconducting Tokamak Advanced Research) project, Instrumentation and Control (I&C) of the Neutral Beam Test Facility (NB-TF) has been striving to answer diverse requests arising from various facets during the project's development and construction phases. Hard-wired electrical circuits have been designed, tested, fabricated, and finally installed to the relevant parts of the system. In relation to the vacuum system I&C, controlling functions for the rotary pumps, a Roots pump, two turbomolecular pumps, and four cryosorption pumps have been constructed. I&C for the ion source operation are the temperature and flow rate signal monitoring, Langmuir probe signal measurements, gradient grid current measurements, and arc detector circuit. For the huge power system to be monitored or safely operated, many temperature measurement functions have also been implemented for the beam line components like the neutralizer, bending magnet, ion dump, and calorimeter. Nearly all of the control and probe signals between the NB test stand and the control room were made to be transmitted through the optical cables. Failures of coolant flow or beam line vacuum pressure were made to be safely blocked from influencing the system by an appropriate interlock circuit that will shut down the extraction voltage application to the system or prevent damages to the vacuum components. Preliminary estimation of the beam power through the calorimetric measurement shows that 87.9% of the total power of the 60kV/18A beam with 200 seconds duration is absorbed by the calorimeter surface. Most of these I&C results would be highly appropriate for the construction of the main NBI facility for the KSTAR national fusion research project.

Keywords: Arc detector circuit, Beam energy, Calorimeter, Gas feeding system, Interlock circuit, Ion source monitoring, Neutral beam injection

1. Introduction

In order for the NB-TF (chamber dimension: 3M x 4M x 5M; part of it is shown in Picture 1) to operate properly, there must be many functions to support the system. Vacuuming, power supply for the ion source operation, coolant water circulation, gas feeding to the system, operation of the beam line components such as the neutralizer, bending magnet, and calorimeter, and beam diagnostics are some of those functions. I&C is another significant function, one that has been supporting the NB-TF from the initial stage of development and construction [1], in particular, hard-wired I&C.

Examples of the hardwired I&C are vacuum system control and monitoring, brazing furnace support for the ion source development, ion source monitoring, I&C for the gas feeding system, bending magnet control works, and temperature and flow rate measurement at various locations of the beam line [2]. As there are many electrical potential barriers in the system, most of the signals between the control room and the facility itself have been made to be transmitted through the optical fiber cables. For the safe and failure-free operation, integration of the interlock circuits to the system operation has also been accomplished.

Recently, there has been collaborative work between KAERI and JAERI (Japan Atomic Energy Research Institute); and the JAERI ion source was performance tested at KAERI from August to October in 2005. The extracted ion beam was 60 kV/18A, 200s. This long duration of beam extraction at the beam power is remarkable in the road to the final goal of 300 second operation.

All these experiences and expertise of the hard-wired I&C are expected to be well applied to the upcoming construction and operation of the main NBI facility incorporated to the KSTAR.

2. Temperature Measurement and Calorimetry

2.1. Utilization of thermocouples

Most of the temperature measurement needs were met

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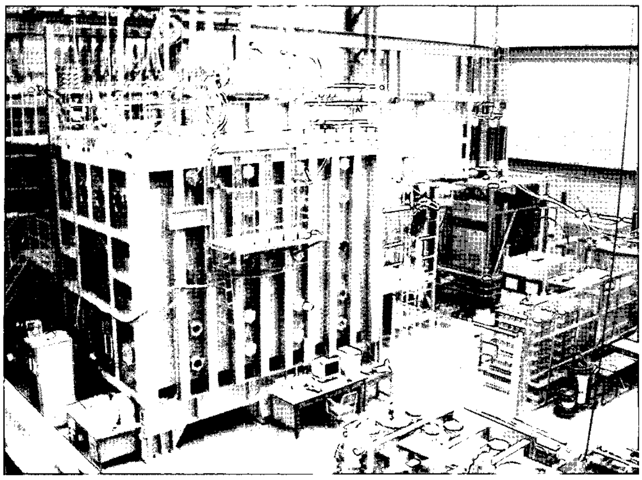


Picture 1. Main chamber of the Neutral Beam Test Facility Constructed in KAERI

utilizing many K-type thermocouples, and in a particular case a T-type thermocouple was also utilized for the verification of the calorimeter outlet temperature measurements. Signal readings from TCs were achieved through the utilization of the National Instruments' SCXI-1102 and were sent to PXI-1101 on the DC potential region and then sent to the control room at AC GND where the PXI-8176 embedded controller finally processed the signals. There were some thermocouples whose signals were processed by dedicated readout/controller modules other than the above-mentioned NI's SCXI and PXI system; an example is controlling the baffle temperature and the LN_2 level during the operation of the four cryosorption pumps. On some occasions when it was inappropriate to use any readout functions, the thermocouple signals were processed with the dedicated AD595 chip, which processes thermocouple signals and then outputs 10mV/℃.

2.2. Pt-100 resistance temperature detector

Two conspicuous advantages of the Pt-100 resistance temperature detector (RTD) over the thermocouples are that in the case of the Pt-100, the cold junction is unnecessary and higher stability with wider linearity is possible. A temperature measuring module "TZ4ST-R4C" supplied by AUTONICS was considered fitting to our purpose. Since we should supply the temperature signals to the differential amplifiers, we obtained signal voltage – temperature characteristics of the modules when we connected a 250Ω resistor across the output of the module to determine the performance characteristics. (Fig. 1)

The above result clearly indicates that

$$y = 0.04x + 1.000 \qquad (1)$$

Here x is the temperature signal input and y is the voltage output from the readout. Thus, a 1℃ difference would correspond to 40 mV in voltage difference. The temperature signal voltage was applied to the A/D converter of the National Instruments' PXI system and then sent to the control room through the fiber optic cable. The received signal could then be processed for the temperature values and for the estimation of the absorbed beam powers.

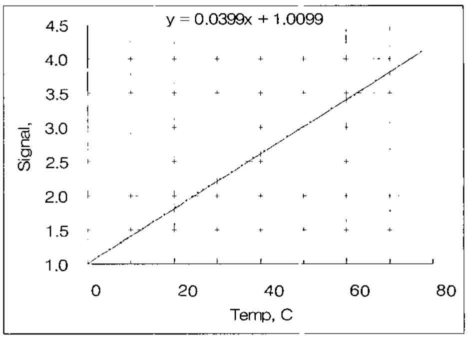


Fig. 1. Voltage signal vs. temperature characteristic of the "TZ4ST-R4C" PT-100 readout module supplied by AUTONICS.

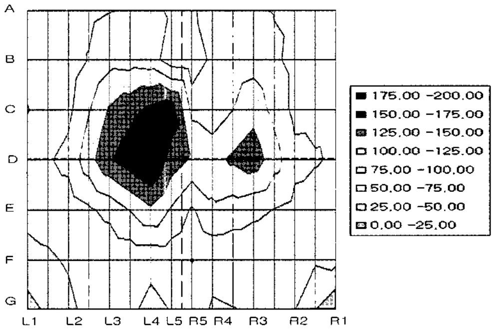


Fig. 2. Calorimeter temperature distribution for the beam condition of 60 kV/18 A, 200s

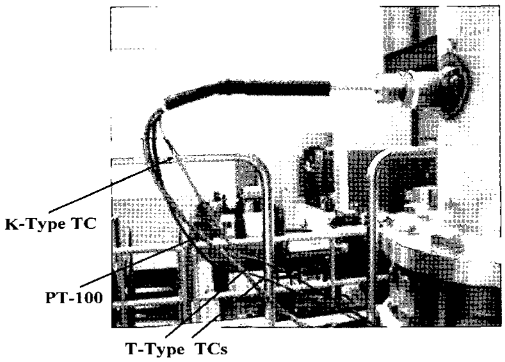
2.3. Beam focusing and power estimation

Recently the NB-TS operation reached to 60 kV/18 A for up to 200 seconds. These beam powers are absorbed at various beam line components of the NB-TS such as the neutralizer, bending magnet, and calorimeter. The calorimeter has two functions to perform; one is to check the beam focusing and the other is for the total power estimation emitted to the torus region. The surface of the calorimeter is hit by the ionic or neutral beam and the temperature distribution is an indication of the beam focusing. From the measurement of temperatures of the sixty K-type TCs installed on the calorimeter surface, a temperature distribution of the calorimeter was obtained as shown in Fig. 2. According to the figure, the beam is inclined slightly to the left. The less hot surface on the right side could be the result of radiation from the hottest surface on the left. This conclusion can be supported by some similar results when the surface temperatures were measured. However, further verification would have to be performed in the future.

The calorimeter should be on the beam path to the main KSTAR Torus, and a desirable proportion of the beam power absorbed at the calorimeter to the total beam energy should be much more than 80%. To check the energy absorbed at the calorimeter during the beamline experiments, the basic relationship for the calorimetry as given by the following equation can be utilized [3, 4]:

$$Q(kcal) = mc\int_{0}^{\infty} \Delta T(t)dt \qquad (2)$$

Here m is the coolant flow rate (kg/sec) and c is the specific heat (1kcal/kg-℃), ΔT = temperature change (℃) while dt is the time increment in seconds. To measure the power absorption at the calorimeter, temperatures were measured at the inlet and outlet of the calorimeter. For sorting out the most desirable temperature probe for the calorimeter experiments and for cross-checking purposes, a K-type TC, two T-type TC and a PT-100 resistance temperature detector (RTD) were installed into the outlet pipeline from the calorimeter (Picture 2).



Picture 2. Temperature sensors installed into the outlet pipeline of the calorimeter

An example of the resultant temporal change of the calorimeter surface temperature is shown in Fig. 3. A beam extraction experiment with the JAERI ion source resulted in data with the energy recovery rate of 87.9 % at the calorimeter as presented in Table 1.

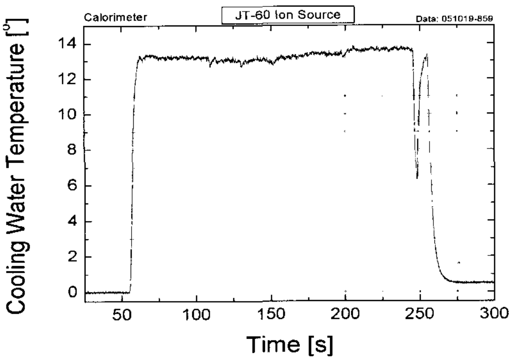


Fig. 3. Temporal change of surface temperature of the calorimeter for the beam of 60 kV/18 A, 200s extracted from the JAERI ion source.

Table 1. Obtained data for the energy recovered by the calorimeter during the beam extraction with the JAERI ion source (Nov. 14, 2005)

Parameter	Obtained Values
Extraction Voltage	60.2 kV
Beam Current	17.7A
Input Energy	210 MJ
Energy by Calorimeter	185 MJ
Flow Rate	16.2 liter/sec
Percentage Recovery	87.9%

3. HARD-WIRED I&C FOR NB-TF

3.1. Optical signal transmission

Most of the sensor signals and control signals of the NB-TF experiments should pass through the various potential barriers [2]; thus optical means of signal transfer has been accomplished for the entirety of the project by adopting optical signal conversion and its transmission through the optical cables. Examples of optical signal transmission are those for the Langmuir probe signals, gradient grid current signals, gas flow control and flow rate signals, ion source temperature signals, beam line component temperature monitoring signals, and coolant flow rate signal transmission, etc. These optical signal transmission provisions are now performing part of the indispensable functions for the proper operation of the NB-TS facility and are well explained in reference [1].

3.2. Vacuum system

Various hardwired I&C supports are necessary for the operation of the NB-TF vacuum system; two main areas are 1) Electrical power supplies for the various pumps and overload protection measures and 2) Control of the valves connecting each of the vacuum components and the monitoring of the valves status. Many pumps are used for the operation of the NB-TF; they are three rotary pumps (each with 2.2kW/3φ) for the basic vacuuming needs, a Roots pump system for the initial evacuation of the NB chamber, two turbomolecular pumps each for the main NB chamber and the optical multichannel analyzer (OMA) chamber, and four cryosorption pumps inside the chamber. A schematic diagram for the outer side NB-TF vacuum pumping system is shown in Fig. 4.

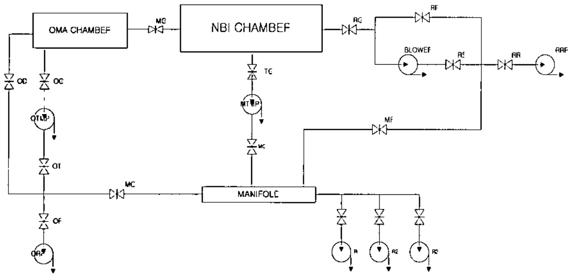


Fig. 4. The external vacuuming components of the NB-TF

A. Rotary action pumps

Of the many pumps that are used in the NB-TF vacuum system, rotary pumps and the Roots pump system are based on the rotary action of the motors. A dedicated power supply module incorporating many magnetic switches and electronic overcurrent relays (EOCR) was installed for the necessary power of the basic vacuum needs. For now, rotary pumps attached to the manifold are provided with their necessary running powers from this module. In a pump process that uses motors for their operations, the most important point to be checked is the running currents that should strictly be within each of their rated values. For such needs to be met without failure, all of the pumps adopting the motor actions were equipped with EOCRs that can cut the abnormally high currents flowing into the motor before any of the overheated states occur.

A Roots pumping system (Stokes, 6", 615 M series Blower accompanied with Stokes Model 212 rotary pump) that acts by collection of air mass from the vacuuming chamber before the conventional rotary venting stage was installed for the swift evacuation of the NB chamber in the initial stages of the vacuuming. This system needs a power of 440V AC(3Φ), 46A for its operation and was also protected by the EOCRs from any of the possible over-current failures. The system also necessitates a large space and makes heavy noise with vibrations, so an attached pump house to the main facility building with some noise and vibration dampening measures was built to accommodate the blower and the rotary pump as well as the accompanying electrical hardwired works.

Even with the large evacuating capacity of the installed Roots pumping system, it soon became apparent that the extremely large volume of the NB chamber (3m X 4m X 5m) overrides the Roots pump action when we attempted to operate the blower at the initial testing stage of the system, resulting in an enormous current of over 190A, which is far larger than the safe operating current. Thus, as a guess for safe time duration before the blower to start its operation, we gave 30 minutes for the rotary pumps to operate as a preparatory vacuuming. The result showed safe operation of the blower without surpassing its rated operational conditions.

B. Turbomolecular pumps

Two sets of turbomolecular pumps are installed in the NB-TF vacuum system: MTMP (Osaka Vacuum, TG2820) attached to the main chamber and the OTMP (Varian, TV 1101) attached to the OMA chamber. These pumps are supplied of the necessary powers from any of the general power lines at the DC GND.

C. Cryosorption pumps

Four cryosorption panels (1.75m X 1.75m; 10^5 L/sec/m^2) [2] are installed within the NB chamber and the accompanying compressors (two *COOLPAK* 4200s and two *ULVAC* C40s) for each of the cryosorption panels were laid and fastened on top of the NB chamber. After a large LN_2 supply tank (5000 Liters) has been constructed for the cryosorption pump operation, LN_2 level control and baffle temperature measurements were accomplished by the installation of various valves onto relevant locations as schematically shown in Fig. 5. For each of the cryopanels, there is a distribution valve V_D in the front end of the LN_2 reservoir, exhaust valve V_G on top of the reservoir, and a valve V_B on top of the baffle.

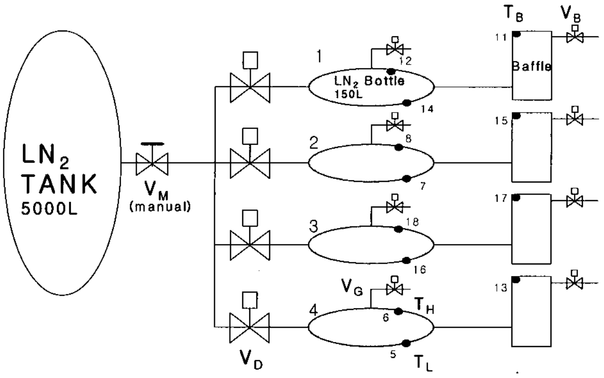


Fig. 5. Schematic diagram of the newly constructed LN_2 supply system.

One notable feature of the system is that each reservoir has two temperature sensors installed onto the high level position (T_H) and onto the low level position (T_L). Thus when temperature T_L becomes higher than the preset value (-190℃), the reservoir was presumed empty; whereas when the temperature of T_H became lower than the preset value, the indication was that the reservoir was full of LN_2. This reasoning for the LN_2 level and the necessary valve action is expressed in a schematic diagram shown in Fig. 6.

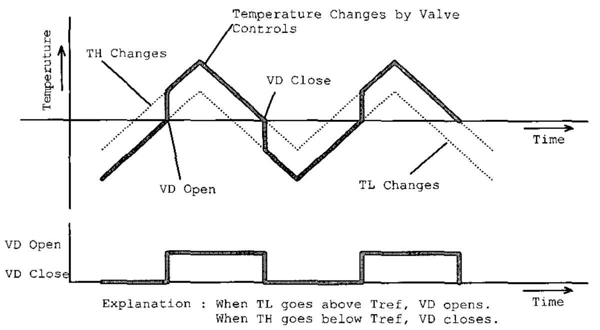


Fig. 6. Temporal schematic diagram of the level control of each LN_2 reservoir

For the baffle temperature control, a temperature sensor installed onto the upper part of each baffle functioned to control the two valves installed on top of the baffle and on top of the connected reservoir. Thus, when the temperature T_B was lower than the preset value (-185℃), V_B was closed and synchronously the valve V_G was opened. When the temperature was higher than the preset value, the opposite action was made to occur, resulting in a piled nitrogen gas pressure that would thrust LN_2 into the baffle region in order for the cooling action to take place.

The resulting circuit related to the controlling level is designed as indicated in Fig. 7. For the case of the baffle temperature control, an apparent feature is that at any time one of the two valves VB and VG would be open to prevent N_2 pressure accumulation inside the reservoir/baffle paths, thus resulting in a complementary actuation of the two valves. The designed circuit for the baffle temperature control is revealed in Fig. 8. A higher resolution temperature controller model (Chino, LT450) was utilized for a more refined control of the LN_2 levels in the reservoirs, whereas for the baffle case controller (Chino, LT230) the temperature resolution requirement is less than the reservoir case. Incidentally, the values of the preset temperatures were operationally obtained in prior tests. The resultant controller according to this reasoning was constructed and finally installed onto the system [5].

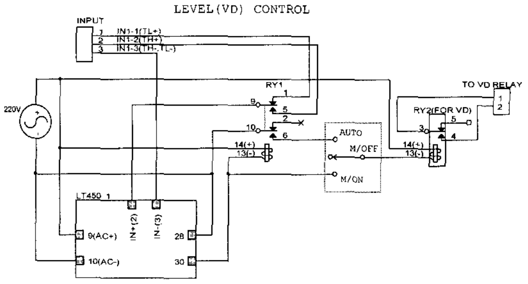


Fig. 7. LN2 level control circuit diagram.

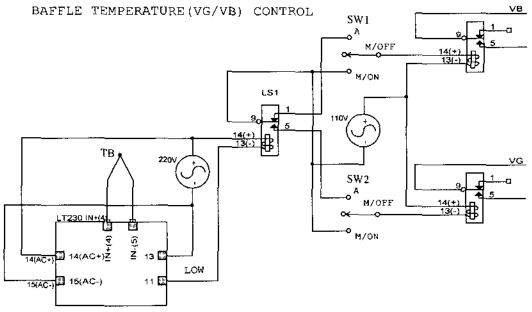


Fig. 8. Baffle temperature control circuit diagram.

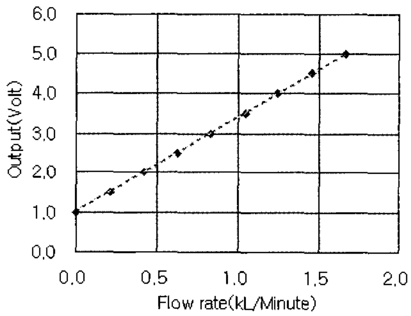


Fig. 9. Output voltage of the flow meter as a function of the flow rate.

4. Interlock Circuit

As the NB-TF experiments approached their final stage, ion beams produced during the tests had taken on enormous proportions in both power and energy: 60 kV/18 A for 200 seconds. With this extent of power and energy, an inadvertent shutdown of the coolant circulation could be devastating, especially on the calorimeter. Vacuum failures could also be deteriorating to the various components comprising the system, or even dangerous because on some occasions resultant liquid nitrogen consumption could become incongruously massive. All these concerns led to the designing of an appropriate interlock circuitry which is to protect, first of all, the calorimeter and the vacuum components of the NBI facility.

4.1. Calorimeter and the cooling line

A rotor type turbine flow meter was installed onto the inlet of the coolant water supply for the calorimeter. The measuring principle of the flow meter is that the rotor blade cuts the magnetic pick-up, which in turn generates a frequency output signal that is directly proportional to the rotor speed. The frequency is then converted to the voltage signal that starts from 1 volt when there is no flow at all. A signal from the flow meter was utilized for the interlock command generation that would shut the acceleration power supply down and also close the gate valve connecting the beam line and the ion source chamber. The output signal data of the flow meter as a function of the flow rate is indicated in Fig. 9.

From the plot of the figure, we get a relationship between the flow rate and the out voltage as follows;

$$V = 2.4 \bullet F + 1 \qquad (3)$$

or

$$F = 0.417\,(V - 1) \qquad (4)$$

where F = flow rate in kiloliters/minute and V = output in volt. From the above equation we made an electronic circuit that sets an interlock signal off under a voltage lower than the set value. For the convenience of the beam line operator, we made the value of the flow rate itself to be the controlling one. Thus we designed an electronic circuit such that the readout value is the same as the flow rate. Through reference of the Johnson's book [6], a circuit implementing these conditions was designed as shown by Fig. 10. In this circuit, hysteresis elements were incorporated to suppress the possible fluctuation of the output from the comparator stage. The hysteresis voltage range was arbitrarily made to 50 mV (or 21L/min by flow rate), according to the following relationship [7]:

$$\Delta V_T = V_{TH} - V_{TL} = \frac{R_1}{R_2}(V_{OH} - V_{OL}) \qquad (5)$$

Here ΔV_T is the hysteresis range we want, $V_{OH} - V_{OL}$ is the difference between each of the op amp saturation voltages, R_1 and R_2 are the input resistance and the feedback resistance, respectively. A final module adopting this electronic circuit for the interlock signal generation was fabricated and installed onto the relevant location.

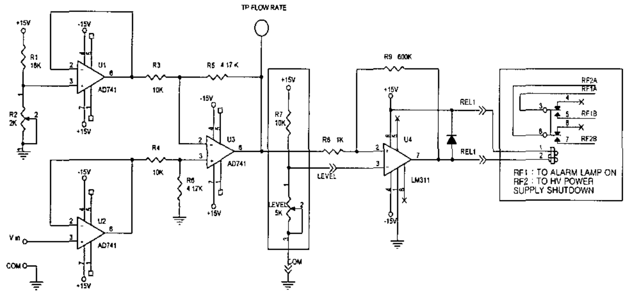


Fig. 10. Designed electronic circuit utilizing the flow rate signal for the interlock of the high voltage power supply and the gate valve closure.

4.2. Vacuum failure and its interlock measures

Vacuum failure is another detrimental element to the system. Three vacuum levels were designated as dangerous, and the corresponding interlock measures were implemented as shown in Table 1.

Table 1. Necessary interlock actions for the different abnormal pressure ranges.

Emergency State	Pressure (mbar)	Interlock Actions
VE1	>0.001	Alarm lamp ON
VE2	>0.01	-I/S valve close -Compressors off -LN2 supply valve close -LN2 bottle vent valve open
VE3	>0.05	TMP GV close

According to the emergency vacuum levels shown in Table 1, interlock circuits have been designed, constructed and finally installed into the system. The main section of the interlock circuit is indicated in Fig. 11.

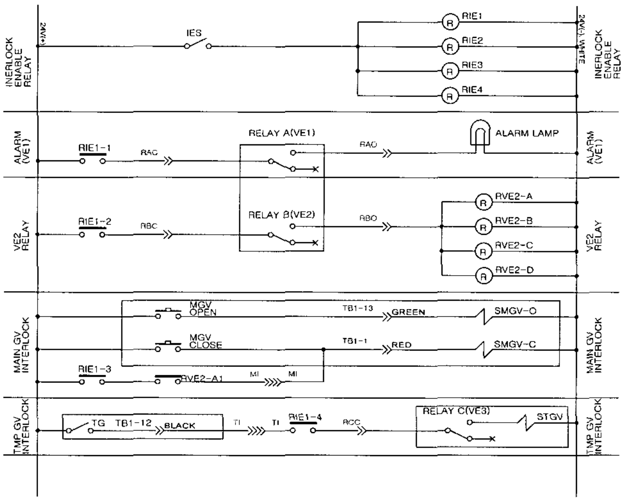


Fig. 11. Main part of the interlock circuit for the vacuum emergency

5. CONCLUSION

I&C for the NB-TF has been performed from the beginning of the KSTAR project, which began in 1998. Vacuum control and monitoring, gas feeding system, ion source monitoring and arc detection, bending magnet operation, beam line monitoring and interlock circuit implementation are some examples of the hard-wired I&C works. Most of the control signal and sensor signals were made to be transmitted through the optical cables between the control room and the NB test stand. Interlock circuits were designed and thereby fabricated mainly for the coolant flow failure and the vacuum failure. A particular experiment with the JAERI ion source resulted in an energy recovery of 87.9% for a 60.2kV/17.7A of beam extracted for 200 seconds. Most of the experiences and expertise of those hard-wired I&C works and interlock circuitry implementation are expected to be well applied to the upcoming main NBI facility for the KSTAR project.

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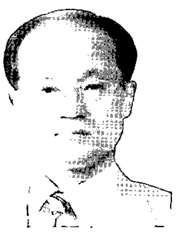

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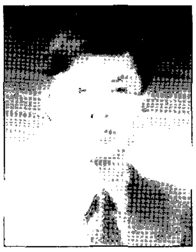

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