KIEE International Transactions on Electrical Machinery and Energy Conversion Systems, Vol. 5-B, No. 3, pp. 289~295, 2005

# Development of Optical Signal Transmission for the KSTAR Project Pertaining to Instrumentation and Control of the Neutral Beam Test Stand at KAERI

**Ki Sok Jung**† and **Byung Hoon Oh***

**Abstract** - Instrumentation and Control (I&C) of the Neutral Beam Test Stand (NB-TS) Facility at the Korea Atomic Energy Research Institute (KAERI) for the Korea Superconducting Tokamak Advanced Research (KSTAR) project has been underway since the start of the project to answer the diverse requests arising from the various facets of the development and construction phases of the project. Optical signal transmission constitutes a significant portion of I&C works and has been performed for the entirety of the project. During the NB-TS construction and related experiments, significant achievements to a more accurate as well as more refined optical signal transmissions have been made. Examples of those I&C works that utilized the optical signal transmission are the Langmuir probe signal transmission, gradient grid current signal transmission, gas flow control and signal transmission, ion source temperature measurement, beam line component temperature monitoring, and coolant flow signal transmission, etc. These optical signal transition provisions are now performing part of the indispensable functions for the proper operation of the NB-TS facility. Attained experience and expertise are expected to be well applied to the upcoming main neutral beam injection (NBI) system construction for the KSTAR project.

**Keywords:** capacitors, inductance measurement, Maxwell-Wien bridge, resistors, standards

## 1. Introduction

For a huge physical facility such as the KSTAR-NBI with a final goal of 8 MW, and a required operation time of 300 seconds in order to work properly, there must be various supporting functions for the system (1). I&C is one of those functions, supporting the NB-TS development and construction works from the project initiation in 1998 (2). Even though there were works for the software-oriented I&C for the NB-TS facility, demands for the hard-wired I&C work should have been met throughout the project. Vacuum control and monitoring, a gas feeding system, ion source monitoring and arc detection, bending magnet operation, and implementation of the interlock circuitry are some of the examples of the hard-wired I&C works for the NB-TS.

One of the essential parts of the NB-TS is the ion source; it consists of four electrodes designated as plasma grid (G1), gradient grid (G2), decele-ration grid (G3), and exit grid (G4). During operation, G1 is applied with the highest voltage, G2 with the next highest voltage, etc. G4, where the beam line chamber also resides, is at the same potential as the high voltage return line, which is designated as DC ground. For the suppression of the "ground loop" current, a "one point" conducting connection has been established between the DC ground (i.e., G4) and the AC ground where the facility building and the control room are constructed.

The ultimate operational goal of the NB-TS is to apply a high voltage of about +120 kV to the G1 electrode, with an expected ion current of about 60A, for 300 seconds; presently we are working up to 80 kV-20A for about ten seconds (3). This high voltage, large current application for extended time duration has been imposing demanding works concerning the control signal application and the measurement of the experimental signals from various locations of the system. Of the many aspects of the hard-wired I&C between the high voltage barrier of the ion source and the AC ground where the operating personnel resides, the most apparent one has been that the ordinary metal-wire based signal transmission is not applicable. Thus naturally the optical means have emerged to be indispensable throughout the whole period of the NB-TS project. Especially after the completion of the control room, which was constructed at AC ground with 40m distance (by the conduit line length) from the 60 $m^3$ (3M X 4M X 5M) NB test chamber that was constructed to the DC ground in autumn of the year 2002, optical signal transmission became even more important for the various signal transfers between the chamber and the control room.

---

† Corresponding Author: Nuclear Fusion Research Laboratory Korea Atomic Energy Research Institute PO Box 105, Yusung, Daejeon, Korea 305-600 (ksjung@ kaeri.re.kr)

* Nuclear Fusion Research Laboratory Korea Atomic Energy Research Institute PO Box 105, Yusung, Daejeon, Korea 305-600

Received December 6, 2004 ; Accepted July 14, 2005

Presently, nearly all of the controlling and probe signals between the NB chamber itself as well as the ion source and the control room are sent through the optical cables, and there have been existing works related to the refinement of the optical methods and improvement of their reliabilities. At this moment of the final stage of the NB-TS experiments, it is appropriate to detail the practical aspects of the optical signal transmission and critically assess the optical circuits installed at various locations of the NB-TS at KAERI.

## 2. Basic optical signal transmission circuits

### 2.1 Optical converter using the ADVFC32

At the beginning of the works for the optical signal transmission, a voltage to frequency (V/F) as well as frequency to voltage (F/V) converter integrated circuit (IC) commercially named as ADVFC32 supplied by Analog Devices was used for the signal transmission through the voltage barriers. The circuit utilizing this kind of VF-FV conversion technique is fairly simple; with only a few passive components attached to the IC for both the transmitter and the receiver board. Components for the optical signal transmission and reception were the TX176 and RX176 supplied by Toshiba, which are for the ESCA type plastic optical fibers. As only a few components are necessary for each channel, we can accommodate many channels compared to the other circuit, which adopts the analog to digital (AD) conversion technique as will be explained later. We designed and manufactured printed circuit boards (PCBs) with dimensions of 10cm x 12cm (transmitter) and 10cm x 14cm (receiver), respectively, each accommodating 5 channels as shown in Fig. 1. As can be seen in the Fig. 1, the plastic optical fiber (POF, the usual ESKA type) is utilized for the signal transmission.

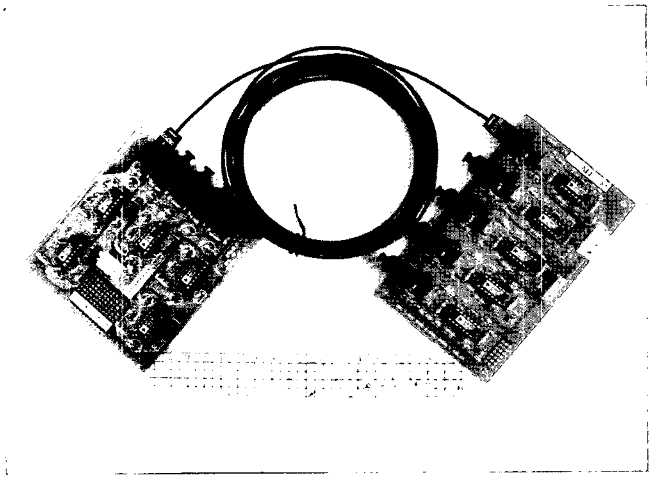


**Fig. 1** The optical transceiver set made of the ADVFC32 V/F and F/V converter for the signal transmission

### 2.2 Optical converter using the AD7891

#### 2.2.1 Fabrication of the circuit

The other optical transceiver circuit we used was based on the PCBs that adopt the AD7891 analog to digital (A/D) converter (12-Bit, 1.6 $\mu$s conversion time) and the parallel to serial transformation of the digitized signals for the optical transmission (Fig. 2). Serialization of the digitized signal was made by using a programmed Altera EPM7064 CPLD chip, which was supplied by the DAWONSYS Co. The receiver board accepts the serial data, deciphers the serialized signals, differently programs the CPLD chip and then transforms the digital signal to reproduce the original analog signal by using the AD667 digital to analog (D/A) converter. The fabricated optical transceiver circuits accept signals anywhere between -10V and +10V. Some of the optical transmitter properties are given in Table 1. This transceiver circuit is designed to accommodate any of the plastic fibers or silica fibers for the transmission. The fiber shown in Fig. 2 is of silica type.

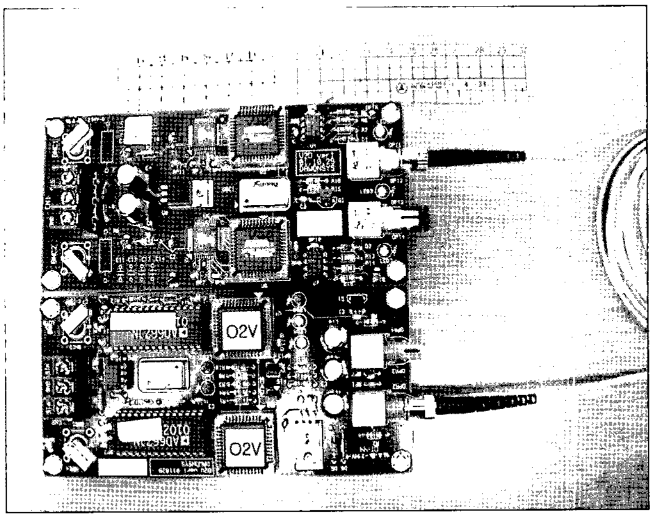


**Fig. 2** An optical signal transceiver set using the AD7891 AD converter and CPLD chips for the signal conversion and transfer. The upper board is the transmitter whereas the lower one is the receiver.

**Table 1** Some of the silica core optical fiber based optical transceiver board properties.

| Properties | Values |
|---|---|
| Input voltage | +/- 10V |
| Bandwidth(3DB Frequency) | 15kHz |
| Resolution | 12 Bit |
| Maximum Distance | Silica fiber[1] : 0 to 500 m |
| Minimum Radius of Optic fiber | 50mm |

Source: Agilent Technologies, Application Note 1080.

### 2.2.2 Performance of the circuit

After some utilization of the optical transceiver boards at various locations of the NB-TS, it became apparent that there existed some discrepancies between the input and output signal levels of the transceiver circuit. For example, the measurements of the input and output for any pair of transceiver boards showed typical output values of about 97.0±0.3% when compared to the input voltages. There were also offset voltages when the input voltages were zero, usually with tens of millivolts of offset voltages. Up until recently, these discrepancies of the output voltages were regarded as acceptable. However, as the NB experiments have been progressed, necessities to refine the data reproducibility and offset calibration have emerged. For the improvement of the data reproducibility and offset calibration, as the corresponding databook(4) suggested, two variable resistors were inserted into the original receiver board as shown in Fig. 3. This refinement resulted in typical outputs of 100.1±0.2% and satisfactory zero offset values when compared to the original input voltages, and these values are now considered as satisfactorily acceptable within our experimental requirements (See Table 2). Incidentally, measurements of the fast-changing signals were also made; generally the output signal came out at about 80 $\mu$ sec after the input signal application. This value would have to be considered when measuring fast changing signals.

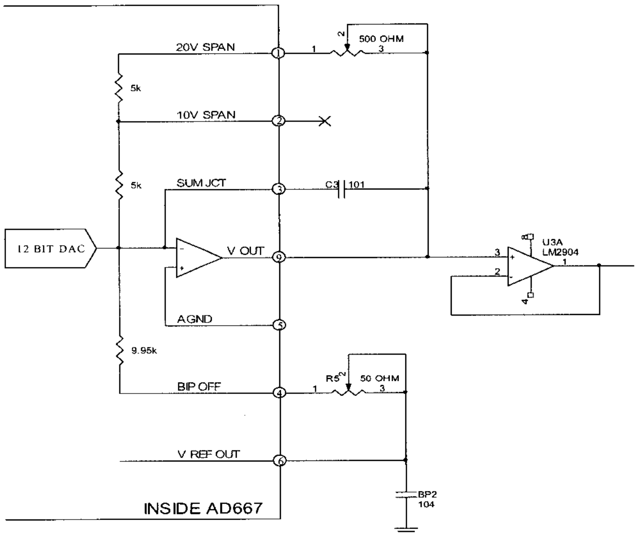


**Fig. 3** Two variable resistors inserted around the output and the related pins of AD667 for the refinement of reproducibility and offset calibration.

**Table 2** Result of the signal reproducibility test for the refined optical transceiver circuit

| Input(V) | Output(V) | % | Input(V) | Output(V) | % |
|---|---|---|---|---|---|
| -10.000 | -10.004 | 100.0 | 1.000 | 1.001 | 100.1 |
| -9.000 | -9.004 | 100.0 | 2.000 | 2.005 | 100.3 |
| -8.000 | -8.005 | 100.1 | 3.000 | 3.003 | 100.1 |
| -7.000 | -7.007 | 100.1 | 4.000 | 3.997 | 99.9 |
| -6.000 | -6.006 | 100.1 | 5.000 | 5.000 | 100.0 |
| -5.000 | -5.004 | 100.1 | 6.000 | 6.008 | 100.1 |
| -4.000 | -4.007 | 100.2 | 7.000 | 7.009 | 100.1 |
| -3.000 | -3.005 | 100.2 | 8.000 | 8.015 | 100.2 |
| -2.000 | -2.008 | 100.4 | 9.000 | 8.994 | 99.9 |
| -1.000 | -1.006 | 100.6 | 10.000 | 10.000 | 100.0 |
| 0.000 | 0.000 | 100.0 | Average | | 100.1 |
| | | | Std Dev | | 0.2 |

### 2.3 Comparison of the different optical circuits

As can be seen in Table 3, the most apparent feature of the AD7891- based optical signal transmission is that it is designed to be connected with a silica type (Hard Clad Silica, HCS) optical fiber that can deliver signals at least to 500m (5), whereas the ADVFC32-based optical transceiver circuit with the POF can deliver signals up to about 60m, according to the corresponding data book(5). However, within our experiences, signal transmissions became unreliable or even impossible when the distance reached 40m for the POF cases (Fig. 4). This situation happened when we completed the control room to which about 40m of conduit lines had to be connected from the NB test chamber, and this is the very reason why we changed the optical transceiver boards from the POF based ones to the HCS based ones. Incidentally, Fig. 2 indicates significant delayed signal output with the rising time of about 5 msec; about 10 msec is required to get the full output of the input signal. This time delay is quite large when compared to the AD7891-based circuits with HCS that show about 80 $\mu$ sec for the full recovery of the input signal.

**Table 3** Comparison of some characteristics between the two types of optical transceiver board types

| Category | Board Type | |
|---|---|---|
| | ADVFC32 based | AD7891 based |
| Input signal range | 0 to 10V | -10V to +10V |
| Delivery distance | Up to 50m(POF) | At least 500m(HCS) |
| Dimension | 5 ch / 10cm x 10cm (Tx board) | 2ch / 7cm x 15cm (Tx board) |
| Power Consumption | +/-15V, Negligible current / 5Ch | +/-15V, ~250mA / 2 Ch. |
| Assembly Cost | ~ 20 $/ch | ~ 30$/ch |

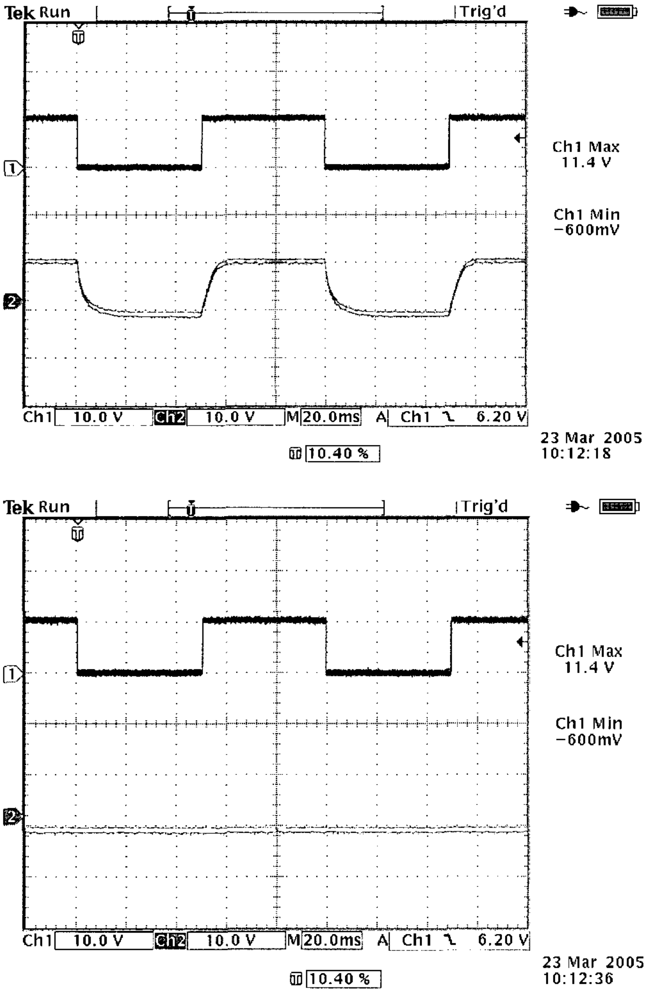


**Fig. 4** Result of the signal reproduction test for the POF-based optical transmission circuits. Waveform A is the result with POF of 30m while waveform B is for 50m POF. Result B indicates the impossibility of signal reproduction at the receiver board

Even though we no longer adopt POFs for the optical signal transmission, thus not utilizing the ADVFC32-based board any more, this type of board still has some favorable characteristics worth consideration. That is, it is more economical to assemble and simple in circuit design, it accommodates more channels per unit area, and can be redesigned to accommodate the HCS parts to make the reaching distance longer. Also, a bipolar signal transmission would be possible if some appropriate voltage offsetting is made to the circuits. Contrary to this advantage of ADVFC-based optical boards, AD7891-based boards consume a great deal of power for their operations: 250mA/+15V for TX board and 190mA/+15V for the RX board. This large power consumption is a severe disadvantage for the G2 current measurement circuit, which must be powered by batteries for its operation. Contrary to the AD7891-based board, the ADVFC32-based circuit consumes negligible power.

## 3. Installation of optical signal transmission circuits onto the NB-TS

### 3.1 Langmuir probe signal measurements

Langmuir probe signal measurement is one of the most important diagnostic methods for the plasma densities in ion source operations; in our case, eight sets of Langmuir probes were installed. For the low level signal measurements from the Langmuir probes and the accompanying signal transmissions, we adopted preamps and optical transceiver boards. The preamp input was differential and the output was isolated from the input signals using an ISO122P isolation amplifier. The board dimension was 10cm x 17cm and its output was then fed to the usual optical transmitter–optical receiver pair previously shown in Fig. 4.

### 3.2 G2 current monitoring

#### 3.2.1 Earlier version

Current flowing through the G2 electrode can be indicative of the beam optics inside the ion source. This current, which is usually less than 100mA, can flow from the plasma inside of the ion source to the power supply, or vice versa; so current signals can be negative as well as positive. Thus, on the initiation of the circuit design, the optical transceiver PCB circuits based on AD7891 were considered suitable for these needs. As there was no available AC power for the G2 area, we had to adopt a battery powered circuit for the current measurements. In order to be accommodated into the restricted G2 area, the circuits should have been fabricated as small as possible. Thus, we adopted a TL431 reference voltage generator in coordination with the use of a voltage comparator for regulated voltage monitoring. However, this circuit was found to be unnecessarily complex, and the space reduction was not as significant as expected.

#### 3.2.2 Newer version

One of the most severe problems of the earlier G2 current measurement circuit had to do with the batteries used to provide power to the circuit. The battery was a conventional lead acid battery that was very heavy, had low ampere-hour characteristics, and poor quality, probably resulting from the dubious product origin. So we recently adopted a "Toshiba" 1.2V Ni metal hydride (Ni-H) rechargeable cell for driving the G2 current monitoring circuit. Two sets each with 20 of these batteries stacked to make about 27V were made for supplying power to the voltage regulator circuit of the G2 current measurement circuit. The initial charging test showed the ampere-hour value of this pile to be about 2A • H. This value was considered sufficient for a circuit consuming 0.25A for its operation, thus it was expected that 8 hours would be allowed between battery changes. This is significant, as the G2 area is located high on the voltage dividing tower and access is not easy. Also, the TL431 for the voltage checking purpose was replaced with much simpler, classic analog meters. Fig. 5 shows the internal view of the transmitter module of the newly made G2 current measurement circuit.

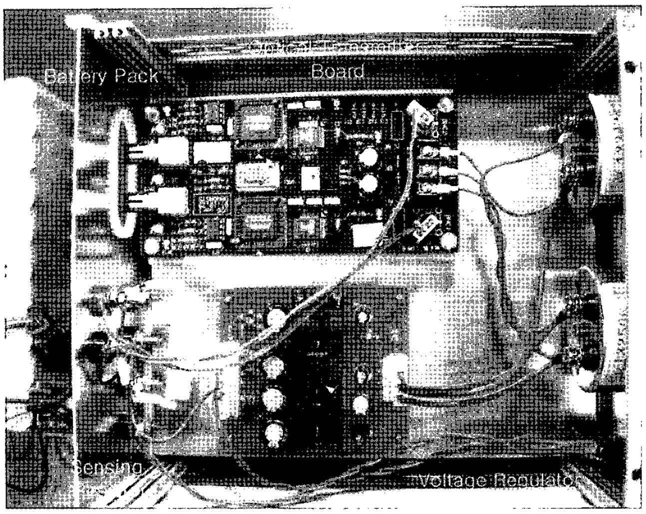


**Fig. 5** Internal view of the fabricated transmitter module of the newer version of the G2 current measurement circuit.

### 3.2.3 Consideration of the further refinements

Even though the newer version of the G2 current monitor used a lighter, more reliable Ni-H battery for the regulator power supply, utilization of it soon revealed that the Ni-H batteries showed unsatisfactory characteristic of charge/discharge cycle. That is, Ni-H batteries usually displayed deteriorated ampere-hour characteristic each time the charge-discharge process was performed. All these problems related to the batteries basically rooted on the heavy power consumption of the AD7891-based optical transceiver circuit; i.e. this circuit draws the necessary power for the +5V from the regulated +15V, which is made from the battery powers. As far as this power consumption element exists inside the circuit, considerable burning up of precious battery power seemed unavoidable.

Thus, the circuit utilizing VF/FV conversion adopting the ADVFC32 for the G2 current measurements has been reconsidered. However, some modifications of the circuit should be made on the circuit if we want to utilize it. First, as the G2 current can be bipolar and the VF/VF circuit only covers the positive polarity, a voltage offsetting function should be made to exist at both transceiver ends. Secondly, as the reaching distance of the POF is inadequate for our situation, HCS type components should be utilized.

## 3.3 Optically isolated gas flow controlling circuit

Gas feedings to the NB-TS components also require isolated signal transfers between the control room and the controlled elements. There are two NB-TS components that require isolated gas feeding; they are the ion source and the neutralizer. The gas flow controller readout module, for which we are using the MKS Model 247D, is made to be controlled or read remotely by an optical signal communication. After utilizing the POFs connected to the ADVFC 32-based optical transceiver circuits for some time during the earlier phases of the NB experiments, we faced deterioration or impossibility of the optical signal transfer when we tried to extend the optical line from the experimental locations to the newly constructed control room that is about 40 meters distant by the conduit line from the NB chamber. This was soon reasoned to be the result of the inability of the POFs to send signals for such an elongated distance, and switching to the HCS type optical fibers made it possible to communicate between the two locations. A typical HV module that receives the gas level controlling signals and sends the gas flow rate signal is shown in Fig. 6.

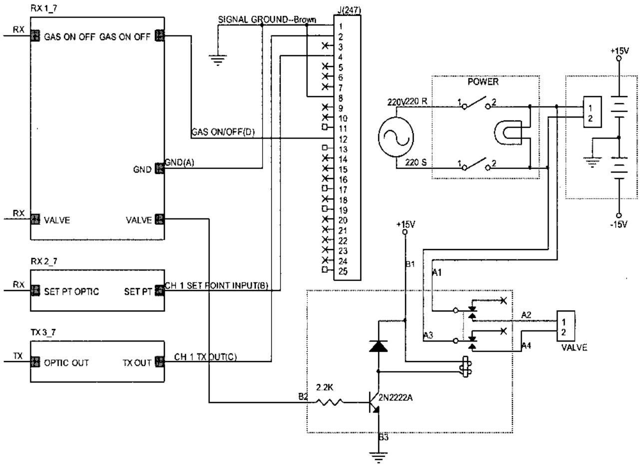


**Fig. 6** A typical schematic diagram of the HV module for the gas flow control circuit

## 3.4 Temperature and flow rate monitoring of the ion source

During the ion source operation, electrons back-streaming from the G4 electrode contact the electron dump, which is at the same potential as the positive electrode of the arc power supply, causing the electron dump surface to be even hotter. This heated surface could deform or damage the structure and the cooling channels imbedded within the structures, besides generating some degree of X-rays. Thus, monitoring the temperature of the electron dump surface and the coolant flow rate was concluded to be imperative by optical means. The measuring sequence is that first the thermocouple signal is amplified to a directly readable temperature signal using the PCB circuit utilizing AD595 as shown in Fig. 7. As the flow rate signal between 0 to 7.5l/min should be made to be 0 to 10V at the reading stage, the signal from the flow meter is fed to an appropriate op amp circuit as shown in the Fig. As there is no available power to drive the monitoring circuit in the electron dump area, an isolating transformer was adopted to receive the necessary power from the negative filament area, which is also at the G1 potential.

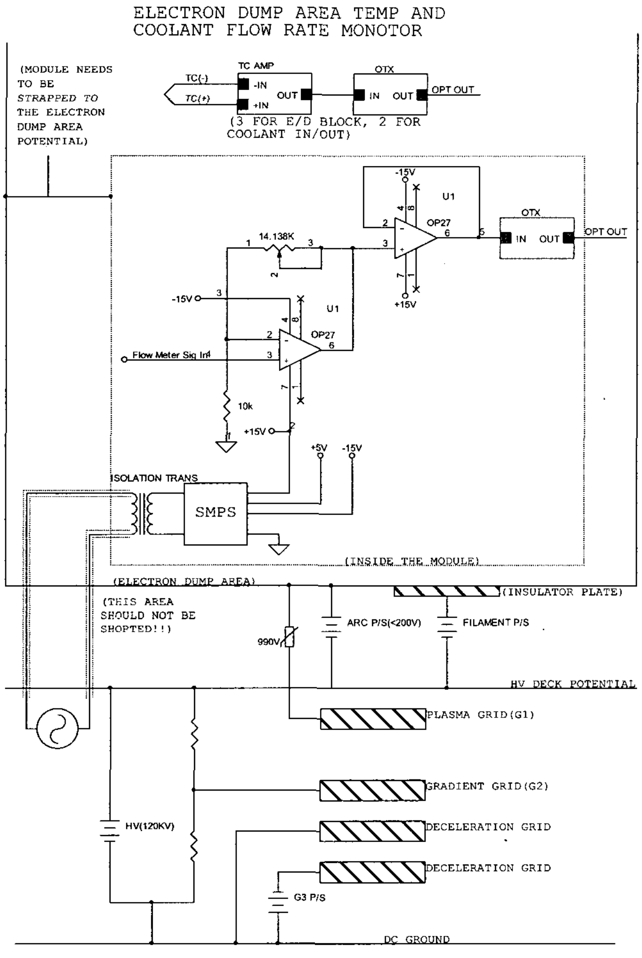


Fig. 7 Electron dump surface temperature and coolant flow rate monitoring circuit using the AD595 thermocouple amplifier and the optical signal transceiver

### 3.5 National Instruments' PXI system

National Instruments (NI)' PXI data acquisition products are also utilized in the system. PXI-1000B is installed in the control room and PXI-1011 is installed in the G4 area as shown in Fig. 5. As indicated in the Fig., only a pair of optical cable covers all the necessary signals to and from the control room. Currently, this system is dedicated for the measurement of 101 thermocouple signals from the ion dump (15ea), neutralizer (8ea), bending magnet (8ea), calorimeter (60ea) - all of them in the G4 area. Another nine signals (in volts) are coming from the flow meters; thus a total of 110 signals from the G4 area are fed to the control room PXI system. It should be apparent that there exists extensive multiplexing of the signals in the NI PXI system. The apparent advantage of this system is the usage of only one pair of optical cables compared to ours, which needs one optical cable for each signal. We are considering another installation of the PXI system in the G1 area. This would greatly reduce much of the signal lines, thus lessening the burden on the signal conduits.

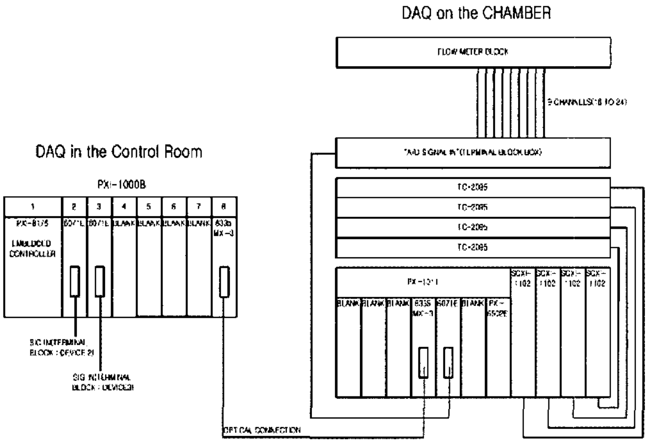


Fig. 8 Layout of the DAQ components for the NBI system.

## 4. Conclusion

Status and experience of optical signal transceiver circuits for the NBI signal transmission are detailed with an emphasis on the evolutionary aspects of the works during the NB-TS developmental period. Some of the optical signal transceiver circuits that we have been utilizing are compared by their respective characteristics. Performance refinement related to the data reproducibility and offset calibration is accomplished with satisfactory results within our experimental necessities.

Considering that the preamp circuit has only one channel/board, the Langmuir probe signal measuring sequence utilizing a preamp and the optical transceiver pair takes up much space in the precious high voltage deck. Thus for a 19 inch standard rack we can only accommodate ten channels of the preamp circuits. The preamp circuit uses a few integrated circuits including OP27. However, some components could be replaced by an instrumentation amp that can accommodate many of the functions achieved by the usual ICs such as OP27. Also, as the high voltage deck of all the components and instruments are at the same potential, a possibility of eliminating the isolation amps could be investigated. However, as the Langmuir probe signal is differential in nature, a use or non-use of the isolation amp would have to be considered carefully. If we make a new optical transmitter board that has the preamp circuit using an instrumentation amp like IN118, for which we have experience of its utilization (6), only a small increase in the number of components would make the optical transmitter board equipped with the preamp function, thus eliminating the preamp module in the high voltage deck.

For the G2 current monitoring, the heavy, dubious quality lead-acid battery was replaced with much lighter, reliable, and durable Ni-H battery packs and the unnecessarily complex circuit was simplified. However, a further possibility of lesser power consumption for the G2 current monitoring is again raised by suggesting the adoption of the VF/FV conversion method with voltage offsetting and HCS components adoption. The usage of a PXI data acquisition system is explained with the consideration of utilizing another PXI set in the ion source area in the near future.

## References

[1] "Development of Heating System" for Korea Superconducting Tokamak Advanced Project (KSTAR), KAERI/RR-2252/July, 2001.

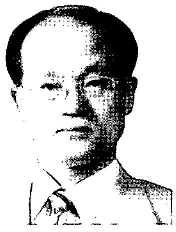
[2] "Fabrication and installment of the hard-wired I&C Works for the Neutral Beam Injection system of the KSTAR Project", Proceedings of the Korean Nuclear Society Spring Meeting, Gyeongju, Korea, 2004.

[3] "Design Initiation of the Interlock Circuitry for the KSTAR-NBI Facility", Kisok Jung, et. al., 2004 Korean, Nuclear Society Meeting, Yongpyung, Korea, October 2004.

[4] "AD667: Microprocessor-Compatible 12-bit D/A Converter", Analog Devices.

[5] "DC to 10 MBd Versatile Link with Plastic Optical Fiber or Hard Clad Silica Fiber (HCS) for Factory Automation and Industrial Control Applications", Application Note 1080, Agilent Technologies.

[6] Byung Hun Oh, et. al., "Development of the Pirani and Penning Vacuum Gauges", KAERI/RR-1978/99, Dec. 31, 1999.



**Ki-Sok Jung**

He has been working for KAERI from 1977 and received his PhD degree in inorganic chemistry in 1989 at the graduate school of Choong-Nam National University. He is working on the hard-wired instrumentation and control for the neutral beam test facility(NB-TF) which will be the prototype for the NB of KSTAR national fusion research project.

**Byung-Hoon Oh**

He has been working for KAERI from 1987 and received his PhD degree in nuclear fusion engineering in 1996 at the graduate school of Hanyang University. He is managing the project for the development of NB heating system for the KSTAR national fusion research project.