T.1 Enhancements in Indus-2 Control System for Machine Performance Improvements

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The Indus complex, RRCAT is a synchrotron light source laboratory consisting of four electron accelerators, a Microtron, a Booster synchrotron, a 450 MeV storage ring, Indus-1 and a 2.5 GeV storage ring, Indus-2. Electron beam of 20 mA and 20 MeV obtained from Microtron is transported to Booster synchrotron through the Transport Line-1 (TL-1). The Booster synchrotron boosts the energy of the electron beam from 20 MeV to 450/550 MeV for injection in Indus-1/Indus-2 rings respectively. Extracted beam from the booster synchrotron is injected into Indus-1 through Transport Line-2 (TL-2) and into Indus-2 through TL-2 and TL-3. Indus-1 is operational at its design current of 100 mA.

The accelerator in the context is Indus-2, a 2.5 GeV, 300 mA electron storage ring, a national facility, in operation at RRCAT. It has provisions for total 26 user beam lines coming out from bending magnets and proposed insertion devices. The machine has wide array of subsystems and devices positioned all around the ring in a wide area of approximately 8000 m^2. In a large accelerator facility like this, proper machine operation can only be achieved with effective monitoring and control over an extensive range of devices and subsystems. In Indus-2, the computer control system does this job. The machine is operated from a central control room, while there are provisions for operating some sub-systems from their local control systems essentially in local mode, e.g. RF, injector Microtron and auxiliary systems like cooling water systems. The control system for Indus accelerators is indigenously designed, developed, implemented and maintained by the Accelerator Control Section, RRCAT.

The control system for Indus-2 is an integration of large amount of diversified hardware, software and communication resources on a standard control system scheme [26]. The system, as initially implemented, had basic functionalities, useful features and facilities for machine operation at injection energy, ramping and storage at higher energies. It has played an important role in the commissioning, regular operation and evolution of Indus-2. Evolution of control system has been hand-in-hand with the progress of Indus-2.

The control system is now operational for more than eight years and continuously evolving. Concept of "looking back and improving" has brought many improvements to the control system. Regular internal reviews and addition of new features have helped to evolve the INDUS-2 control system to a state comparable with the control systems of similar configurations across the globe. All the efforts made to bring the systems to this level are indigenous from the local team.

The article discusses the design concepts, the evolution over last few years to its present state and plans for future enhancements [11].

1. Indus-2 Control System Overview

Indus-2 control system is based on client server model, enabling functional and physical separation and placement of hardware and software modules across the entire range of control system components. It is divided into a number of intelligent sub-systems each of which autonomously controls a specific accelerator subsystem. It is a distributed, three tier standard control system architecture [26]. The control system is distributed over three layers (*Fig. T.1.1*), viz.

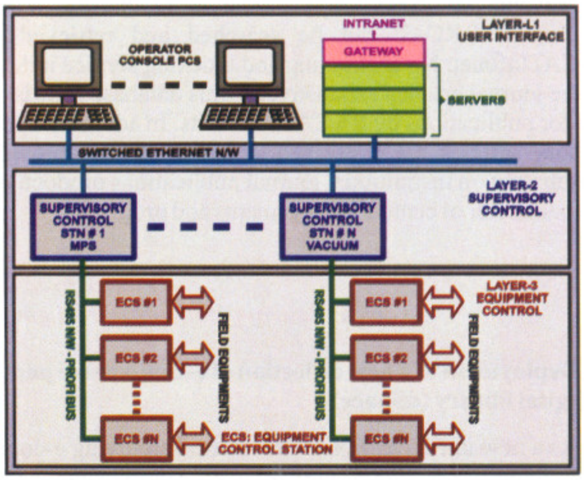


Fig. T.1.1: Indus-2 Control System Architecture

User Interface (UI) layer, *Supervisory Control (SC)* layer and *Equipment Control (EC)* layer. These layers are also called Layer-1 (L1), Layer-2 (L2) and Layer-3 (L3) respectively. L1 directly sees the operators while L3 directly connects to the instruments in the field. L2 & L3 are based on VME controllers running a multitasking real time operating system [21]. Ethernet (100 Mbit/s) and PROFI bus (750 K bit/s) [20] communications are used between L1-L2 and L2-L3 respectively. The modular control system hardware is designed around VME bus. Various VME bus based cards used at L2 and L3 are developed in-house. Figure T.1.2 depicts an Equipment Control Station with three Equipment Controllers having VME boards, developed in-house.

Indus-2 control system handles nearly 10000 I/Os in all. The overall control system is a set of control systems for individual subsystems. These are - Magnet Power Supplies Control System (MPSCS) [23], Pulsed Power Supplies and Timing Control System (TCS) [24], Radio Frequency Control System (RFCS), Vacuum Control System (VCS), Beam Diagnostics Control System (BDCS) [12], Radiation Monitoring Control System (RMCS), Machine Interlock Control System (MICS) [10], Beam Line Front End Controls (BLFE) [9], Low Conductivity Water Control System (LCWCS) [16] etc.

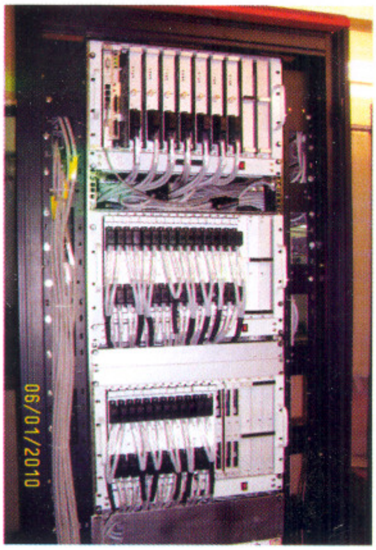


Fig.T.1.2: Indus-2 Equipment Control Station housing three VME Based Equipment Controllers

Individuality of all the control system entities for all the subsystems is brought to a common platform at UI layer. The entities at this layer are the Graphical User Interface (GUI) panels, Server Applications, Application Programming Interfaces (APIs), Web interfaces [25] Database, etc. The identity of individual control system is visible at Layer-2 and Layer-3 by modular approach in the design.

The control system allows the operation of all sub-systems from any console in the main control room. The system is designed such as to minimize the cabling over long runs for minimum interference possibility. The control room sees only essential communication cables and minimum instrument cables brought inside to reduce the cabling clutter and maintenance efforts. To a large extent, operations are achieved with software based panels and switches. The system is essentially modular which renders it to be expandable and easily maintainable. User interfaces are mostly built around a SCADA system (PVSS II) for managing the complex requirements in an integrated manner [5,19].

Initially, the functionalities offered by the control system were sufficient to operate Indus-2 in injection mode, energy ramping mode and storage mode at higher energies. The initial troubles posed challenges and Indus-2 evolved gradually. In the process of getting rid of the troubles, demands on the control facilities increased. Thus the control system also evolved. New requirements kept pouring as the commissioning went along. Flexibility in the control system allowed such modifications so far. Lessons learnt suggested strengthening the system diagnostics. Protection of machine components, ease of operation, system data logging and retrieval, security measures, analysis tools and data presentations are the areas of continuous enhancements. Many new features to the control system are added in these areas.

Control systems for some of the subsystems are essentially monitoring systems e.g., Radiation Monitoring Control System, Vacuum Control System etc. as these do not play an active role in optimizing the injection, ramping or storage of beam at higher energy. On the other hand, operators heavily interact with Magnet Power Supply Control System, Timing Control System and RF Control System for optimizing the beam. Thus the enhancements in the control systems for these subsystems are quite frequent and more frequent than the control systems for other subsystems.

Various enhancements in the individual control systems leading to performance improvements in past few years and in recent times are described subsystem wise.

2. Enhancements in Timing Control System (TCS)

The Injection system of Indus-2 consists of six pulsed magnets i.e. Thick Septum, Thin Septum and four Injection Kickers namely K1, K2, K3 and K4. These are controlled by the Pulsed Power Supplies and Timing Control System (TCS). Additionally, the TCS also controls the timing synchronization of Extraction Kicker and Extraction Septum of Booster in the Indus-2 mode of operation [24]. The trigger system remains active only during the injection and accumulation of beam in Indus-2. Some of the improvements done to the Timing Control System since its inception are described below.

A) Inhibition of Beam Injection in Indus-2

As with all the accelerators, initial efforts were to get the beam injected and its revolution. The role of booster extraction system and Indus-2 injection systems are vital here. This needs tight timing synchronization and accurate delays between various devices of extraction and injection systems. The timing control system was made to handle the accuracy requirements needed for delays and synchronization [24]. Beam decay during initial few turns needed investigations and evolved into requirement of deferring the injection process by stopping the injection system softly. This was achieved by inhibiting the triggers to the pulsed power supplies so as not to give jerk to the revolving beam. The objective was to stop further injection of beam after the desired number of bunches. By doing this, study of first few turns or even the first turn of the injected beam was possible. It became a very handy tool for regular operation not only for the analysis of the beam in the initial stage but also for stopping the injection after desired accumulation of the beam current. Recently, the deferring scheme is changed from separate external circuit and it is now implemented in the main delay boards. Beam injections is now stopped using the soft buttons and this event is also logged to the main database, so that, beam loss, if any, during the deferring can be correlated and studied.

B) FPGA Based Delay Generators [6,8]

The trigger signals to the kickers are synchronized to 505.8 MHz Indus-2 RF clock. Need for this synchronization posed the challenge of tight timing accuracies and jitters on the trigger signals. The trigger generator cards were designed using ECLinPS family. Loss of synchronization was observed frequently due to EMI on account of high power switching from the pulsed devices connected to it. Augmentation of filters and interface isolation helped in reducing these problems but they still remained. All the timing trigger and coincidence generator cards were then redesigned, this time using FPGAs internally operating at 125 MHz. This reduced the cabling and conductive path lengths of different inter-card signals, increased the number of channels per board and reduced the interference problems and jitter further to optimize the performance. Set value readback for delay data was also added. Figure T.1.3 depicts a 5 channel delay generator VME card.

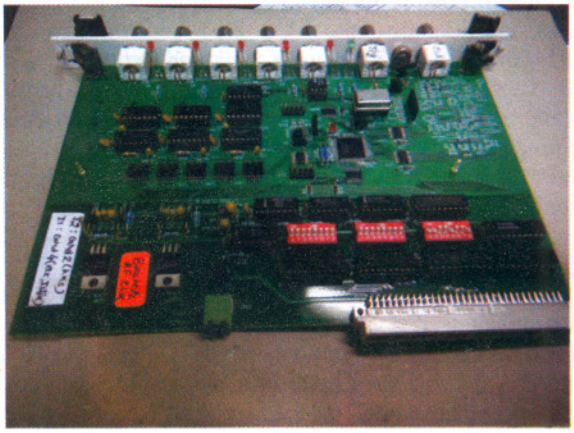


Fig.T.1.3: FPGA Based 5 Ch. Delay Generator Card for Indus-2 Timing Control System

C) Use of Fibre Optic Interface

For quite some time, the pulsed power supplies in the injection system were interfaced to control system with 4-20 mA current loop signals for their reference settings. Later on, the interface scheme is replaced with fibre optic based reference setting scheme for better noise immunity. Complete system isolation is achieved by this. This finally brought the desired performance improvement in the trigger system. This also strengthens the protection of the control system components against possible dangerous and noisy transients due to high voltage discharge in the pulsed magnets and power supplies interfaced to the control system.

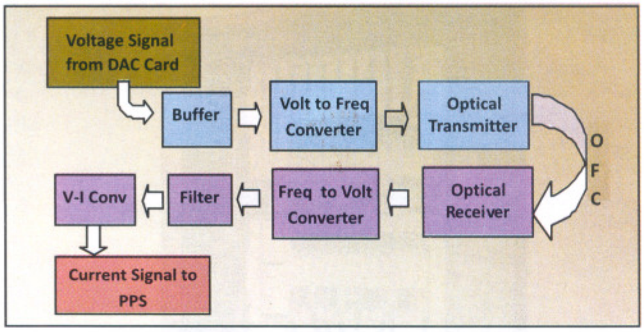


Fig.T.1.4: Fibre optic interface for reference setting

D) Trigger & Delay Diagnostics: Display of Trigger Status and Delay Setting Readback on Control Console

For easier and faster diagnostics, the status of trigger pulses received by the power supplies is added to the control panel in the control room so that non receiving of trigger signal by any of the components of the injection system is known in the control room. Readback of delay settings is also provided on DEBUG panel to check the actual data going to the delay generator cards.

3. Enhancements in Magnet Power Supplies Control System (MPSCS)

Magnetic elements in any circular accelerator directly influence the beam optics and dynamics. In INDUS-2, there are about 300 magnets on the ring doing this job. The magnets are powered by about 180 power supplies. Magnet Power Supplies Control System (MPSCS) plays a vital role in defining and sustaining the required beam with desired dynamics.

The control system with all its functionalities facilitates beam injection and accumulation, energy ramping to higher energy levels and finally long time storage of the beam. Different sets of requirements are posed by the beam dynamics for all these phases of beam operation. The control system is capable of maintaining the power supplies' performance in different modes of operation and caters to the stringent accuracy and stability requirements of 50 ppm up to the power supply input of dipole and quadrupole supplies [23]. Flexible and programmable magnet cycling and synchronous energy ramping [13] are very important features. The ramping system also facilitates ramping of all RF cavity voltages synchronously. After the initial implementation, many modifications were carried out in order to improve the performance of the control system for magnet power supplies. Few glimpses of such enhancements are described.

A) Implementation of Controlled Switching of Magnet Power Supplies

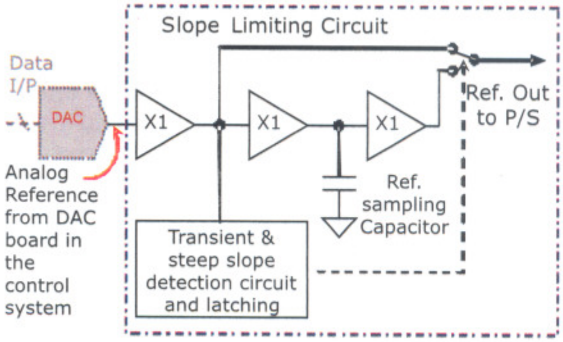
Typical control functions associated with the power supplies are ON, OFF, RESET and SETTING of current. The commands for these actions are issued by different mechanisms i.e., through ON/OFF commands directly issued by the operator, by 'file loading' or by 'shut down all' command etc.

Ill effects of switching the power supplies at higher reference current settings were observed on the power supplies and also on magnets. The abrupt change in the dipole magnetic field causes a sudden jerk to the vacuum chamber passing through the dipole magnet. This may have detrimental effects on the vacuum chamber. Enhancements in the control software were carried out to ensure the controlled switching of power supplies. The software brings the reference signals to its minimum value in a controlled manner before switching it ON/OFF. Reference signal to the power supply is changed with a programmable rate, limited to a maximum allowable value. The supply is switched only after achieving the minimum value. This is called the soft switching of power supplies.

B) Limiting the abrupt changes in the programmed reference to power supplies

Abrupt changes in the magnetic field may also result from the sudden changes in the reference to a power supply in the ON condition. Consequences include, tripping of the power supply, killing of the beam and the destructive stresses on the dipole vacuum chamber. Fixing the causes of the abrupt changes is important but the prevention in such cases is more vital and a primary concern.

Keeping the vitality of the issue in view, an independent 'slope detection and limiting' module is designed to prevent the sudden change in remote reference output signal for dipole magnet power supply reference. As shown in the fig. T.1.5, the 'slope detection and limiting' module is connected to the reference signal output from DAC. The module keeps on sampling the reference and updates a capacitor to the value of reference in normal operation. It also senses the rate of change of the reference and if the rate of change exceeds the fixed limit, it triggers a switch that disconnects the DAC output from the reference output and connects the capacitor output to the reference output. Thus if a transient of more than a certain value appears at the DAC output, the reference output follows the DAC output till it is tolerable. After that, the DAC output is disconnected from the reference output and a reference of approximately same amount is enforced to the output in place. The reference output falls very slowly and thus fast or abrupt change in the power supply current due to reference is avoided. This also prevents power supply tripping. This protection module is designed to maintain the accuracy and stability of 50 ppm provided by the high accuracy DAC module. The tolerable limits of slope and amplitude/ time are fixed in hardware.



FigT.1.5: Scheme of Slope Detection and Limiting Module

A test waveform is attached in the *fig. T.1.6*. Here yellow trace (channel-1) is the reference signal before the slope limiting module and the cyan trace (channel-2) is the output of the slope limiting module. For testing and demonstration purpose, the slope limit is set to 40 mV/ms (corresponding to 4A/ms) and the tolerable rapid change in the reference is set to 0.2 V (corresponding to 20 A). It is clearly visible that the channel-1, i.e. circuit input experienced a large, abrupt voltage rise of about 5 V, while the channel-2 or the circuit output experienced only a limited rise and went back close to its previous value. Thus, it prevents the large abrupt change in the reference. The occurrence of such event is also latched, notified and logged.

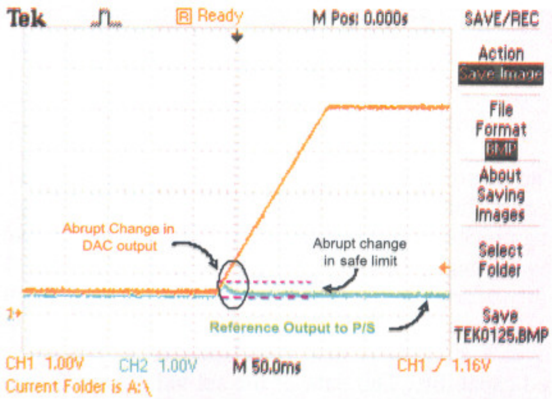


Fig.T.1.6: Test results of the Slope/ Rate Limiting Module

C) Ramp Data Readback & Diagnostic Scheme for Indus-2 Magnet Power Supplies

Overall data capturing rate of the Magnet Power Supplies Control System is 1 Hz. The reference set value at Layer-3, the actual reference given to the power supplies and the readback of current output of the power supplies are recorded at this rate. This is done for all the power supplies. During the DC operation, this rate is sufficient as these values do not change in this mode. However, during the energy ramping process, references for different power supplies, generated at respective L3 stations, are synchronously increased in steps at frequency of 20 Hz to 150 Hz. Thus a system polling data at 1 Hz may miss out any transient data inconsistency occurring during ramping at this higher rate. Such data transients might destabilize the beam or affect the machine performance, which is not straightforward to detect. Partial or complete beam loss during ramping could be a common outcome. For this purpose a ramp data readback & diagnostic scheme (*Fig.T.1.7*) has been developed and incorporated in the MPSCS. This scheme helps in analyzing deviation/transient in the control reference signal and the MPS readback signal during the ramping process. Using this scheme we can capture the data at a rate equal to the rate of clock used for ramping. Also, this data is captured in a synchronized way at various distributed VME stations. Correlation between the data of various supplies can hence be checked.

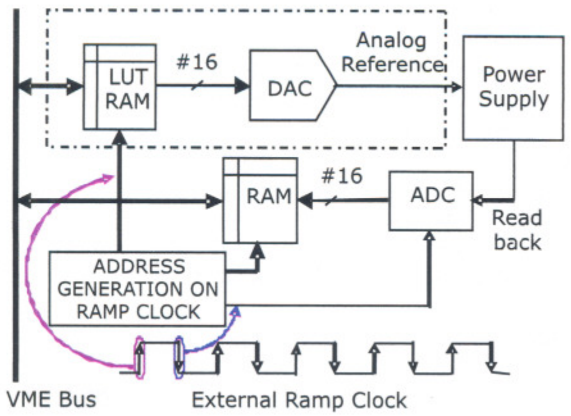


Fig. T.1.7: Ramp Readback Scheme

The control stations at Layer-3 are modified to enhance the system for faster, synchronized readback during the ramping process. The hardware of ADC boards of the control stations are augmented with local buffers and enriched with capability of reading the power supply values synchronously at each increment of the references. Embedded software at all the Layer-3 stations is also developed to incorporate the featured capability. The data of the set value, power supply readback and actual reference output to power supply are all stored in the buffer for each increment during ramping. Captured data can be fetched by the analysis tools at Layer-1 for off-line analysis. This can bring out any inconsistency in the tracking among various references and power supplies during ramping process.

The main hardware used to achieve this functionality consists of VME based 24-bit ADC board and 18-bit DAC board for each of the 29 MPS and a common ramp-clock generator board along with CPU and Profi-bus communication boards.

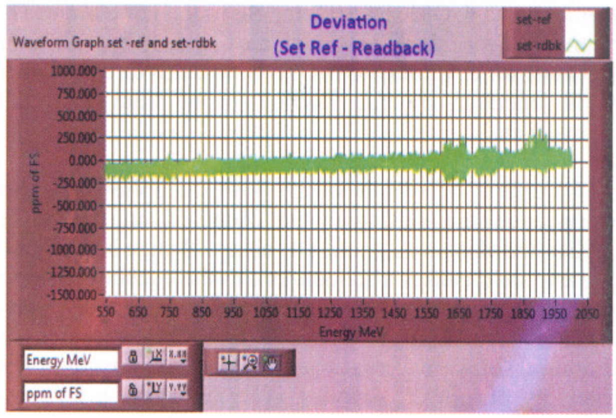


Fig.T.1.8: Deviation of readback from the set reference during energy ramping

A plot of the data captured using this scheme during a typical energy ramping process is shown in fig. T.1.8. This shows the deviation of one of the power supply readback current from its set value during ramping. The deviation is in ppm of Full Scale (FS) against increasing its energy from 550 MeV to 2.5 GeV. The deviation is within ± 250 ppm during the ramping process.

D) Interface Support for Standby Quadrupole Power Supply (QP PS)

A standby QP PS is made available for the Indus-2 ring. In the event of failure of any of the QP PS in Indus-2 ring, an on the spot replacement of the flawed power supply can easily be made by shifting the magnet load connections to a standby QP PS in the MPS hall. For interfacing the control system to this standby power supply, an Equipment Control Station (ECS) at Layer-3 is added with required additions at SC and UI layers. The number of the faulty QP PS is to be set at the GUI panel and the standby power supply is referred by the number of replaced power supply. Rest of the operations on the power supply are transparent to the operator in all operation modes i.e. DC, Ramp, cycling and Group settings. The replacement operation at the GUI is authenticated. This would help to keep the downtime low in such cases.

A) Repeat Last-Ramp (Re-Ramp)Facility

In Indus-2, beam is stored at injection energy and then ramped to 2.5 GeV. Energy ramping requires synchronously increasing the currents of various power supplies and also the cavity gap voltage of the RF cavities [13]. The ramp data is calculated based on the user given trajectory for ramping and stored in the memory of DAC cards at layer-3. The user defined trajectory may change for different ramp operations depending on various factors like tune points, optics, required final beam energy etc. So, earlier it was planned to generate the ramp data for every ramp operation. However, the data generation requires nearly 4-5 minutes for each ramp cycle.

In order to eliminate this ramp data generation time during regular operation of machine, a feature to reuse the earlier generated ramp data has been provided. Operator is required to generate ramp data once and if no modifications (ramping device changes or value changes) are required in next ramping operation, the earlier generated data can be used. The system checks for the integrity of ramp data and confirms if the initial values of the ramping devices are same as that of the last ramping cycle. The differences, if any are notified to the operator. The usage of re-ramp facility is allowed once the differences are within the limit. The operator, in this case, is required to confirm the use of re-ramp feature. In re-ramp, the devices are brought to initial values of the last ramp cycle in controlled manner and further ramping from there can be done.

At injection energy, the beam life time is less than the life time at full energy. The life time is also current dependent. Thus, eliminating the ramp data generation time is important for achieving high energy beam of required current.

F) Special Diagnostics Features added for ECS of MPSCS

- The high accuracy Analog to Digital Converter (ADC) card for Indus-2 uses an intelligent, programmable ADC. The MPSCS was enhanced by providing a feature to change the calibration coefficients from UI layer.
- The ADC and DAC cards for the MPS system require temperature controlled bath to provide required stability. A facility to read, display and log the temperature of the baths was added.

4. Slow Orbit Feedback (SOFB) Control System

Synchrotron radiation sources provide light of very high intensity. Beam Lines (BL) carry the Synchrotron Radiations (SR) from the source point i.e., electron orbit inside the dipole magnet or Insertion Devices (ID) to the experimental stations. In the BL the SR position is highly dependent on the position of electron beam, i.e. the electron orbit. Despite the highly accurate beam guiding systems, the beam orbit drifts due to various factors such as temperature variations, ground vibrations, component aging etc.

Active feedback control systems are needed to correct such variations in order to keep the orbit stable [14]. With the same motto, Slow Orbit FeedBack (SOFB) control system is implemented for Indus-2. The SOFB control system is comprised of integrated system with BPIs reading the beam position data from 56 different locations in the ring and 88 corrector magnets used to deflect the beam towards the reference orbit. The overall SOFB scheme is shown in the *figure T.1.8*.

The SOFB control system comprises of two parts viz. the GUI for the operator interaction and the SOFB server that implements the PID based control algorithm for controlling the beam position in horizontal and vertical plane at 56 locations with correction applied every 20 seconds.

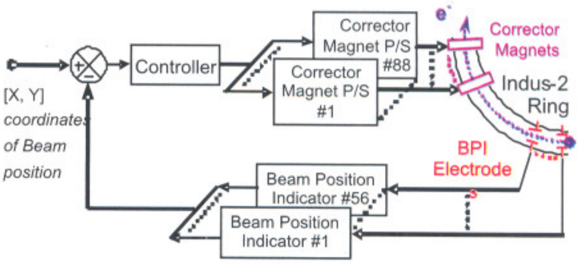


Fig.T.1.8 Scheme of control system for Slow Orbit Feedback System.

The system is enriched with advanced features such as 'agent based model assisted suspected BPI identification' and 'model assisted data prediction' to handle the situation of drift in BPI readings. The system is presently used for providing stable beam of 100 mA at 2.5 GeV for user experiments.

The orbit variations observed in Indus-2 up to ±150 micrometer are now brought below ± 30 micrometers with the SOFB system. Experiments were performed to get the lowest possible RMS orbit and consequently the RMS orbit in horizontal and vertical planes was successfully brought down from 3.12mm and 1.21mm to 0.82mm and 0.55mm respectively.

5. Local Fast Orbit Feedback Control System [14]

Beam orbit variations of the order of 100 Hz occurring due to various noise sources disturb the experiments at beam lines by apparently making the source size bigger. These beam position variations are controlled by separate fast system referred to as the Fast Orbit Feedback Control System (FOFB). Earlier FOFB used to be done for individual beam lines but now-a-days Global FOFB (GFOFB) schemes are possible which can handle fast local corrections globally. Global FOFB is under implementation in Indus-2. As a first step, local FOFB is implemented for beam line-8.

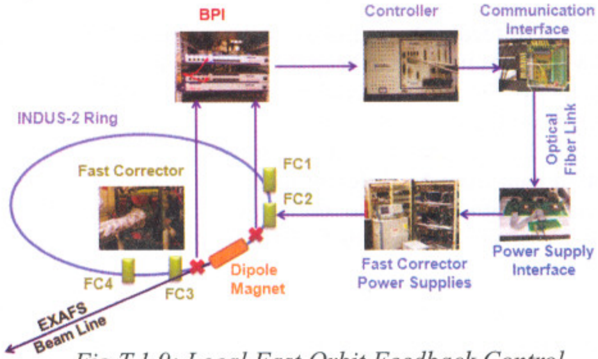


Fig.T.1.9: Local Fast Orbit Feedback Control

In this implementation, electron beam positions on both sides of the dipole chamber for BL-8 are measured using two beam position indicators (BPI). The beam position is controlled using feedback with four correctors (2 upstream and 2 downstream). The scheme used PID controller in both horizontal and the vertical planes with correction applied every 100 micro seconds. The complete system scheme is shown in *fig. T.1.9*.

Orbit variations occurring upto ±30 micrometer in horizontal plane and up to ±9 micrometer in vertical plane in Indus-2 have been successfully brought down to ±3 micrometers in both the planes. Results for horizontal plane are depicted in the *fig. T.1.10*.

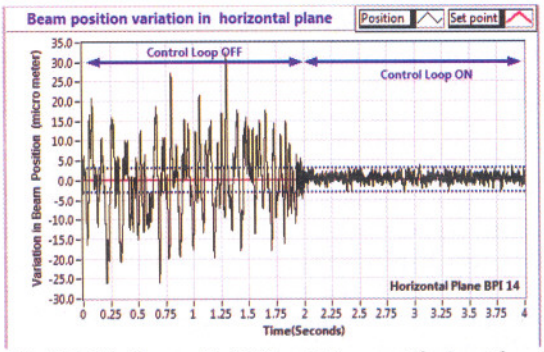


Fig T.1.10: Beam Orbit Deviations with & without Feedback in Horizontal Plane

6. Enhancements in the Beam Diagnostics System (BDS) Controls

A) Software interlock for BPM operation

The beam position monitors (BPM) are pneumatically controlled intercepting type of beam diagnostics devices. BPMs may get damaged if they intercept a high current beam. The intercepting operation of BPMs is interlocked with the magnitude of beam current circulating in the ring in order to protect the BPMs and also to save the beam. The BDS software is enhanced to incorporate this interlock. Enhancement in the software also includes alarm generation when the pressure in the pneumatic line falls below the operational limits and when any of the BPMs get stuck up in intermediate state. This had been found very useful in protecting BPMs as well as avoiding inadvertent beam killing.

B) BPM Operation Counters

The beam position monitors are operated in the vacuum and their life is limited to a certain number of operations. It is therefore important to keep track of the number of operations performed on them. A facility was incorporated to keep a count of number of operations performed on various BPMs in the system. This will facilitate planning in advance for the replacement of the BPMs at the end of life indicated by the operation counter values.

7. Implementation of Tune Measurement and Feedback System

The machine tune value (betatron tune) is an important parameter for accelerator operation. Stability of betatron tune is important factor for stable beam operation. Betatron tune variation may cause reduction in the beam lifetime, reduction in injection efficiency and beam loss if a critical resonance point is crossed. Measurement and correction of betatron tune in both horizontal and vertical plane during the beam operation is thus very important. Tune feedback systems are used to correct such effects. For Indus-2, a tune feedback system (*Fig.T.1.11*) has been implemented by the Accelerator Control Section, Beam Diagnostics Section and Beam Dynamics Lab jointly.

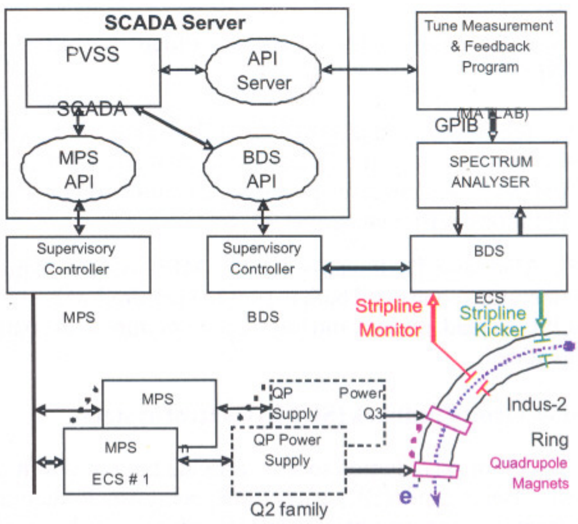


Fig T.1.11: Schematic of Tune Measurement and Feedback System

Indus-2 employs a swept spectrum analyser and a tracking generator based tune measurement system. The tracking generator output is amplified and used to drive strip line kickers in both horizontal and vertical plane one at a time. The BDS controls were enhanced at all the layers of the control system to provide this selection through a multiplexer card.

The software architecture of the control system is enhanced to provide interface to the tune measurement software developed by Beam Diagnostics Section.

The corrections calculated by the tune feedback software need to be applied to the magnet power supplies. The control system software is enhanced by developing an interface application with necessary limit checks to allow setting these corrections to the quadrupole power supplies through the magnet power supply control system.

8. Beam Line Front End (BLFE) Controls

Beam Line Front End (BLFE) is a part of every beam line, which connects it to the accelerator ring. Components mounted on the front end mainly isolate the ring vacuum from the vacuum leaks in the front end and beam line and vice-versa. There are some more protection components in the front ends. Every beam line has a front end and a local control system for its operation. Operation of all the protection components in a BLFE, like vacuum isolation valves, fast closing shutter and safety shutters etc. should be permitted from the local control station only with a prior authentication from the machine control system (control room). The integration of machine control system with BLFE control system allows a well co-ordinated and safe usage of machine by its users at beam lines. It allows the operation of vacuum valves & safety shutters in a coordinated way by local BLFE control systems. The valve operations are interlocked with the vacuum conditions on either side of the valve. Lately, the BLFE control system was enhanced for added machine safety conditions. Revisions thus made are briefly introduced below.

A) Inclusion of controls and interlocking of newly installed pneumatically operated Gate Valves

Earlier all BLFEs had manual gate valves. It was decided to change these to remotely operated type to enable automatic and quick vacuum protection. Pneumatically operated gate valves were installed in place of the manually operated Gate Valves in the BLFEs that came up subsequently. The control system is upgraded to include the operation of the pneumatically operated Gate Valves-0 (GV0). Along with this, the system monitors the pneumatic line pressure also, which is required in proper state for operating these valves. Some of the BLFE components and conditions are reviewed as critical and hence, related interlocks are also taken in Machine Interlock System. In case of some critical conditions in the BLFE, a 'beam dump' signal is generated by the Machine Interlock System. BLFE control software is also enhanced, essentially to provide added protection for BLFE vacuum valves. Under some other conditions, beam injection is inhibited by controlling the septum magnet power supply from the control system. For this, the interlock information is passed to the Indus-2 Timing Control System at user interface layer.

B) Interlocking Beam Line status with beam injection

Additionally, the shutter in Transport Line-3 is closed when the safety shutter in any of the BLFE is open. This also takes care of human safety. The enhancement in the BLFE supervisory control system also includes granting beam line usage permission and logging of various events related to BLFEs and their parameters.

9. Central Alarm Handling System [7]

Indus machines have thousands of parameters which are being logged at different rates. During regular machine operation, system trips and other abnormal conditions are indicated by the alarm handling system on the centralised alarm panel. This system is continuously evolving and after its commissioning, many new user requirements and new sub-systems have been incorporated. Some important enhancements relate to indentifying and prioritising critical alarms, playing special sound file for distinct audio identification and gating the alarms for special system conditions like start-up for avoiding alarm flooding.

Proper machine operation depends on complex relation of a number of parameters which should remain within some tolerance limits. A 'Parameter Deviation Alarms' module was added to cater to this requirement. The system enables keeping close watch on a range of critical parameters for deviations beyond the normal limits and raises the alarm in the control room. Thus, any abnormal deviations of parameters are timely brought to the notice of machine operators for needful action.

10. General Diagnostics and Troubleshooting Features in Control System

Experience from the system operation suggested many ways for reducing the machine down time. Some of them have encouraged the system designers for integrating diagnostic and troubleshooting features. Glimpses of some such efforts follow.

- **Bus error reporting**

Any abnormality or error occurring in the equipment controllers has potential to affect system operation in some way. These need to be known and handled. Particularly the VME bus data communication error at the equipment interface layer (Layer-3) is brought up to the supervisory and the user interface layer. This has brought the diagnostics information from the remote controllers at the lower layer to the control room. This helps in easier identification of the malfunctioning unit for quicker corrective action and much shorter system down time.

- **CPU running status**

Health monitoring of the CPU cards in the remote equipment controllers is also implemented lately. Status of the health is checked periodically while the regular operation of the control systems is carried out. This lets the supervisory controllers at Layer-2 take care of the equipment controllers (EC) under them. An EC, when in hung condition, can be given a RESET on the discretion of the system experts. This has reduced the machine down time for such trivial issues.

- **Communication status of Layer-2 & Layer-3**

For diagnostics of the communication between the Layer-2 and Layer-3 and recording failure data of the PROFI communication, the status of communication is brought to the user or operator console also. This lets the operator know of the problem in the communication and helps the system experts keep watch on it. Required solution like program rerun etc at the supervisory layer can be done in such cases. This is done with the aim of reducing the machine down time due to communication errors.

- **Status of the API Manager**

The Application Programming Interface (API) manager is a program to interface the PVSS SCADA to the SC layer [1,15]. For every subsystem, there is one API manager running all the time. Running status of the API manager is the primary diagnostics information and so, it is brought to the user panel for quick diagnostics.

- **Data Logging Status**

The data of various sub systems are logged to a centralised database, from PVSS SCADA control scripts for some sub systems and for few other legacy sub systems, from their GUI applications. The data logging status, i.e. whether the data logging is properly being done or not, is provided on the GUI panel. This status indicates the status as available on the logging control scripts and also from the database itself by checking the time-stamp of the last logged record.

- **Command Logging Extensions**

The programs at PVSS level are upgraded to provide additional attributes for the command logging and providing an acknowledgement to the GUI panels.

11. Data logging [3,22]

Various machine parameters are logged in the centralised database for off line analysis and system diagnostics. The data logging was implemented since the start of commissioning trials. This history data is very important for understanding the machine behaviour and is widely used. Initially, the fastest data logging rate was 10 sec. During the regular operation of the machine it was felt to have faster data logging for MPS and BDS systems. Based on this, the data logging system was enhanced to provide 1 sec rate for these systems. These two systems have nearly 5000 parameters and logging at 1 sec rate was a challenge. The enhanced logging scheme is based on generating files of one minute data and bulk inserting into the database. The scheme also ensures redundant availability of data in files even if the database or the network link fails.

12. Enhancements for Network Monitoring

Indus-2 control system uses a switched Ethernet for communication between various servers, console computers and supervisory controllers. Proper operation of the network is essential for Indus-2 machine controls. This requires monitoring of data traffic on various ports.

A system log server is configured along with Multi Router Traffic Grapher (MRTG) to log the network port events and their data traffic. This provides an insight to know the malfunctioning port or connected machine and thus helps in quickly identifying and resolving the problem. This improves the machine availability.

In the present scenario of increased threat of virus and intrusion attacks, the network security is highly important for un-interrupted operation of the machine. Considering this, Indus network (AccNet) architecture is enhanced by separating the layer-2 segment and allowing access to SC only from the required machine. The new architecture will also allow us to use a port based network access control feature.

13. Enhancements in Web Applications [2,4,17,25]

Web based data diagnostics tools are developed for various applications, including the need to search and report any abnormalities, occurred just before the beam loss event. Web display applications keep on evolving at a faster pace to cater to ever increasing user requirements. The huge parameter data logged by the data logging applications can be retrieved and analysed based on various requirements. Facilities like a multi-parameter graph display (*Fig.T.1.12*), events when the beam energy ramping is done, online downloading of data in csv formatted zip file are a few to mention.

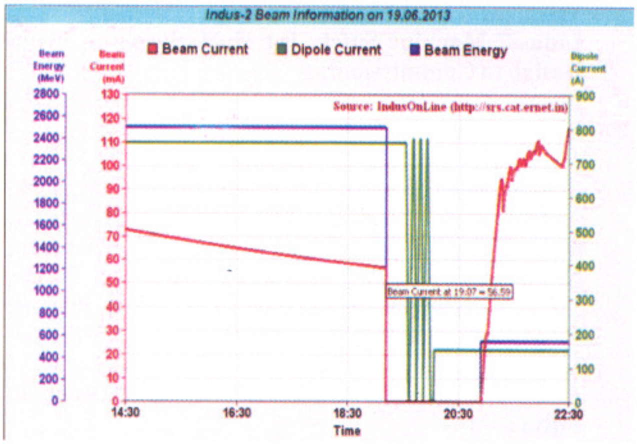


Fig.T.1.12: A Parameter Graph in Indus Online

Apart from machine data, web applications have been added for online logging of faults and generation of fault report and log book. Various such applications include Indus *Online* to provide the live, historical and statistical data to users and system experts, *Fault Information System* for tracking and emailing the faults in sub-systems, *Machine Status Information System* to display the live machine status and any important message entered by machine operation in-charge on large size monitors placed at various locations of Indus Complex, *Flogbook* for logging and emailing the machine faults by shift crew and solutions and comments by system experts, Elogbook [4] to electronically maintain machine operations logbook etc.

These are extremely useful and convenient tools for the system experts, beam line users, machine operators and general users associated with Indus accelerator complex.

Summary and Future Plans

Indus-2 control system continues to evolve and support the ever growing new requirements and enhancements for Indus-2. It plays a crucial role in supporting the evolution of this national facility towards its long term goals. Some very significant future additions would include controls for global fast orbit feedback system, instability feedback system, beam based alignment and various insertion devices. Beam orbit alarms, system readiness display, intelligent machine optimisation systems etc. would add further functional capabilities. The indicative performance improvements of some major control systems and overall control system are clearly visible from *fig.T.1.13*.

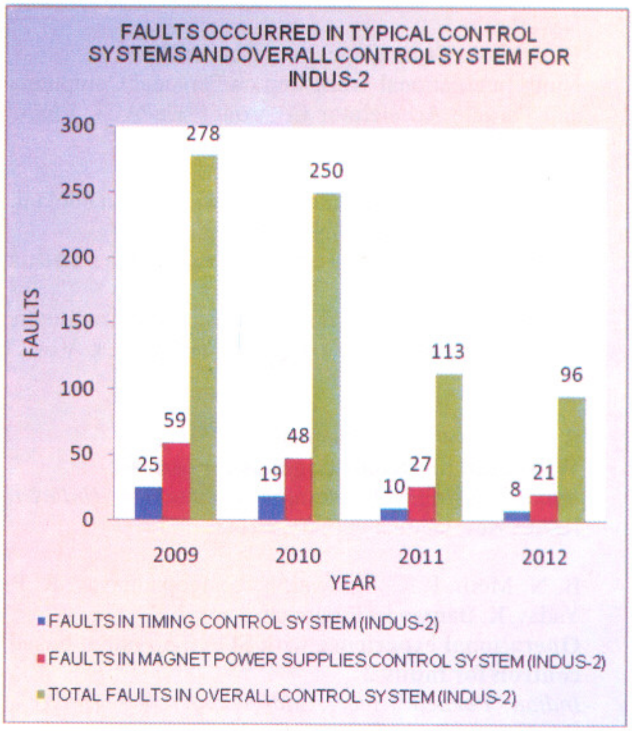


Fig T.1.13: Indus-2 Control System Performance

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