Synchrotron radiation source Indus-1

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The first Indian synchrotron radiation source Indus-1 was commissioned at the Centre for Advanced Technology, Indore in May 1999. The synchrotron radiation from the storage ring Indus-1 operating at 450 MeV extends from soft X-rays to infrared. The injector system for Indus-1 consists of a classical microtron, which accelerates electrons to 20 MeV and a synchrotron, which accelerates these 20 MeV electrons to 450 MeV. Accelerators and their subsystems have been developed indigenously. Here we describe the details of the accelerator facility.

ELECTROMAGNETIC radiation generated by bending the path of electrons moving at speeds close to that of light is called synchrotron radiation. It has emerged as a powerful tool for research in several areas such as material science, chemistry, biology, medicine and semiconductor technology. The increasing use of synchrotron radiation is attributed to its unique characteristics, which include high intensity, natural collimation, tunability of wavelength, high polarization and pulsed time structure.

Considering its widespread utility, it was decided to build two synchrotron radiation sources at the Centre for Advanced Technology, Indore[1–3]. These sources are Indus-1, a 450 MeV electron storage ring for production of VUV radiation and Indus-2, a storage ring of 2.5 GeV for X-rays. In the first phase, which began in 1987, the development of the synchrotron radiation source Indus-1 was taken up. This project involved the development of a 450 MeV electron storage ring and also an injector system which supplies electrons to it. The injector system consists of a 20 MeV microtron[4] and a 450/700 MeV synchrotron. This injector system will also serve as the injector for Indus-2.

The synchrotron radiation source Indus-1 thus consists of a 20 MeV microtron, a 450 MeV synchrotron and a storage ring Indus-1. The layout of the Indus facility is shown in Figure 1. The electrons are generated and accelerated to 20 MeV in the microtron. After extracting the beam from the microtron, the beam is transported to the synchrotron through transfer line-1 (TL-1). A long pulse of 1 μs is injected into the synchrotron; the energy

of the electrons is increased from 20 MeV to 450 MeV. After acceleration to 450 MeV , the electrons are extracted from the synchrotron and then transported to the storage ring Indus-1 through the transfer line-2 (TL-2). This process of production, acceleration and injection is carried out every second till the stored current is 100 mA in the storage ring Indus-1. In the storage ring, the electron beam keeps circulating for a few hours emitting synchrotron radiation continuously in the dipole (bending) magnets.

The synchrotron radiation source Indus-1 involved development of magnets to produce highly accurate magnetic fields, pulsed magnets to produce fast magnetic field pulses, ultra high vacuum system to generate gas pressures as low as 10^{-9} Torr, radio frequency systems for acceleration of particles to millions of electron volts, beam diagnostics devices and control system. All these
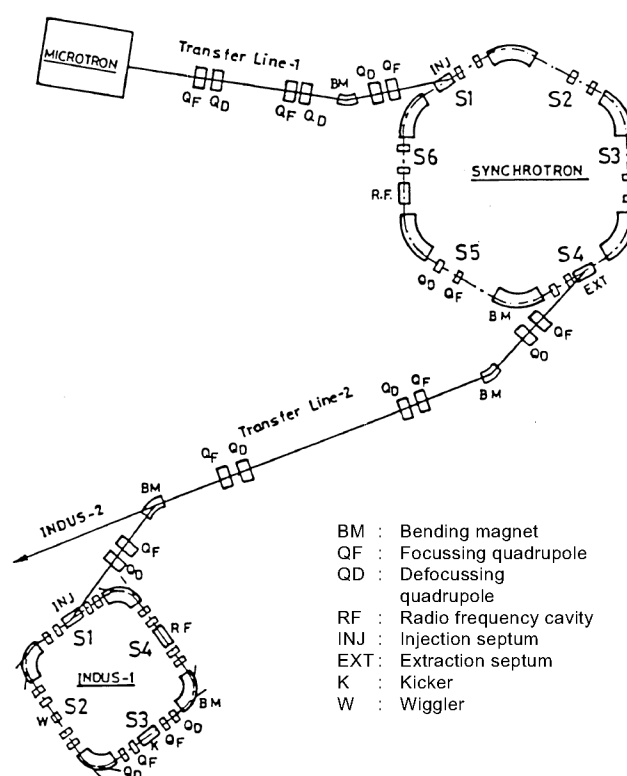

Figure 1. Layout of Indus-1 synchrotron radiation facility.

BM : Bending magnet
QF : Focussing quadrupole
QD : Defocussing quadrupole
RF : Radio frequency cavity
INJ : Injection septum
EXT : Extraction septum
K : Kicker
W : Wiggler

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devices and subsystems have been developed indigenously at CAT and the synchrotron radiation source Indus-1 is fully operational. Presently, many scientists from various laboratories are using it.

Accelerator details

Indus-1 storage ring

Indus-1 is a 450 MeV storage ring designed providing radiation in the range 30–2000 Å. It is a small ring having a circumference of 18.96 m. The critical wavelength (which is defined as a wavelength above and below which the power radiated is equal) of the radiation emitted from its four 1.5 T bending magnets is 61 Å. A 3 T wiggler is planned in this ring to provide the radiation of critical wavelength 31 Å.

The magnetic lattice of the ring consists of four superperiods (repetition of magnetic structure), each having one dipole magnet with a field index of 0.5 and two doublets of quadrupoles[3]. The field index of 0.5 in the dipole magnets helps in achieving a larger stability range because it provides weak focusing in radial and vertical planes. Each superperiod has a 1.3 m long straight section. Two such straight sections are used for beam injection; one section accommodates the septum magnet and the other, diametrically opposite to it, accommodates a pulsed kicker magnet. Of the remaining two straight sections, one is used to accommodate an RF cavity and the other, a 3 T wiggler. The natural chroma-

ticity of the ring, which arises due to different focusing of different energy particles is corrected using a pair of sextupole in each superperiod. The sextupole field gives rise to nonlinear kicks to the beam and tracking studies are carried out to find out which of the particles remain stable after getting several such kicks. The region of stability is called a dynamic aperture and in Indus-1, since the dynamic aperture in the presence of the sextupoles is much larger than the vacuum chamber aperture, the performance of the ring is not adversely affected. Due to the presence of focusing magnets in the ring, an electron oscillates in the transverse planes and the oscillations are known as betatron oscillations. The number of betatron oscillations per turn is called tune of the ring. The ring has a wide tuning range and two tune points have been selected for its operation. The selected tune points are (1.88, 1.22) and (1.55, 1.56). The beam emittance at the first point is much lower than that at the second point. The parameters of Indus-1 at these operating points are given in Table 1 and the lattice functions at one of the tune points is given in Figure 2. Care has been taken to keep the operating points away from the resonances $3v_x = 4$ and $v_x + 2v_z = 4$ which will be excited by the sextupoles. The tune points are also kept away from the resonance lines up to sixth order excited by the periodicity of the machine. Indus-1 photograph is shown in Figure 3.

The circumference of Indus-1 ring has been chosen as 2/3 of that of the synchrotron. The RF frequency of 31.619 MHz provides the electron beam with the additional energy equivalent to the energy radiated by the electrons in the form of synchrotron radiation. It thus keeps the electrons moving on a fixed orbit with a fixed energy.

The beam lifetime considerations, closed orbit distortions and the process of injection govern the vacuum tube requirements. The vacuum tube apertures of ± 30 mm and

Table 1. Parameters of storage ring Indus-1

Energy	450 MeV
Current	100 mA (200 mA achieved)
Critical wavelength	61 Å
Spectral flux (λ_c)	7.2×10^{11}*
Lattice type	Combined function
Circumference	18.96 m
Superperiods	4
Dipole field	1.5 T
Dipole length	1.57 m
Field index	0.5
Quadrupole length	0.2 m
Tune points	
1. (v_x, v_z)	1.88, 1.22
Emittance (ε_x)	7.0×10^{-8} mrad
Momentum compaction	0.142
Spectral brightness (λ_c)[†]	3.1×10^{12}‡
2. (v_x, v_z)	1.55, 1.56
Emittance (ε_x)	2.1×10^{-7} mrad
Momentum compaction	0.316
Spectral brightness (λ_c)[†]	6.4×10^{11}‡
Energy spread	3.8×10^{-4}
Damping times	15.7, 15.7, 7.8 msec
Energy loss per turn	3.6 keV
Revolution frequency	15.82 MHz
Harmonic number	2

*Photons/s/mrad horz./0.1% BW.
†Bending magnet.
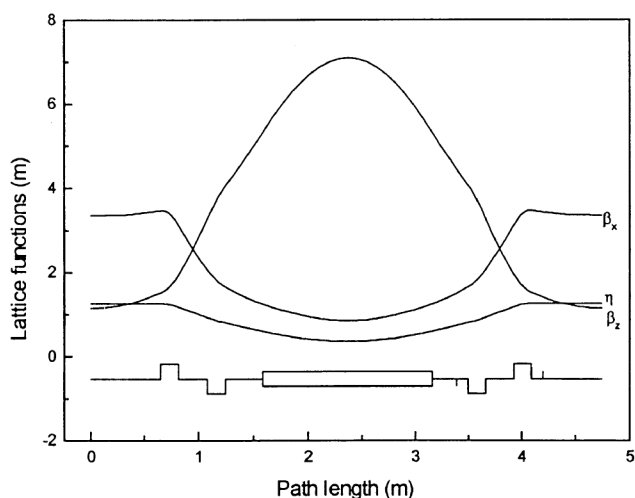‡Photons/s/mm²/mrad² horz./0.1% BW (10% coupling).

Figure 2. Lattice functions of Indus-1 at tune point (1.88, 1.22) β_x and β_z: Amplitude function of betatron oscillations; η: Dispersion function.

± 12.5 mm in radial and vertical planes respectively are found to be adequate. In order to achieve a beam lifetime of a few hours, the pressure in the vacuum chamber in the presence of 100 mA electron beam has to be less than 10^{-9} Torr.

The beam lifetime, i.e. the duration in which the beam current decays to $1/e$ of its value, at 450 MeV is mainly decided by the Coulomb scattering of electrons in a bunch (Touscheck effect) and the elastic scattering of the electrons with the residual gas molecules. The lifetime due to Touscheck effect increases with the energy aperture, the maximum value of which is governed by the longitudinal bucket height, horizontal (physical or dynamic) aperture whichever is minimum. Thus the maximum value of the RF voltage (overvoltage factor) is decided by the physical aperture limitations. The second operating point (1.55, 1.56) is very near to the difference resonance line $\nu_x - \nu_z = 0$ The lifetime due to the elastic scattering with the gas molecules is estimated to be more than 20 h at a gas pressure of 10^{-9} Torr. The harmonic number of the cavity (defined as the RF frequency/revolution frequency) is chosen as 2 to reduce the ion trapping problems.

Injector system

Microtron: The microtron is designed to give a 20 MeV electron beam with a current of 25 mA in pulses of 1 µs duration at a repetition rate of 1–2 Hz. It is a classical microtron having a dipole magnet of 1.4 m diameter, which produces a magnetic field of 1.8 kG with a uni-

formity of 0.2% over a diameter of 0.8 m encompassing 22 orbits of accelerating electrons. The acceleration occurs in a microwave cavity energized by a 5 MW pulsed klystron at 2856 MHz. A LaB_6 pin of 3 mm diameter mounted on a flat face of the cavity is used as the electron emitter. The electrons emitted from the emitter are accelerated to 20 MeV in 22 orbits. The vacuum in the microtron is better than 10^{-7} Torr. The main parameters of the microtron are given in Table 2 and the photograph of the microtron and part of the transfer line-1 is shown in Figure 4.

Synchrotron and transfer lines: The beam from the microtron is transported to the synchrotron through transfer line-1 (TL-1), which has a length of about 14 m. It has three quadrupole doublets and one dipole magnet to take care of the beam parameters as required by the injection process[5]. One 45° dipole magnet is provided to divert the 20 MeV electron beam for some experiments.

The magnetic lattice of the synchrotron consists of six superperiods, each consisting of a dipole magnet to bend the electron beam on a circular path and a pair of focusing and defocusing quadrupole magnets to achieve the required stability and tuning[6]. The maximum magnetic

Table 2. Parameters of the microtron

Energy	20 MeV
Pulse current	25 mA
Pulse duration	1 µs
Repetition rate	1–2 Hz
Accelerating frequency	2856 MHz
Energy spread	0.2%

Figure 4. The microtron and part of transfer line-1.

Figure 3. Storage ring of Indus-1.

Figure 5. The synchrotron.

field of the dipole is 1.32 T. The circumference of the synchrotron is 28.44 m. The main parameters of the synchrotron are given in Table 3 and Figure 5 shows the photograph of the synchrotron. The electrons are injected into the synchrotron by adopting a multi-turn injection scheme using 1 μs long electron beam pulse from the microtron at a repetition rate of 1 Hz. A compensated bump producing a maximum amplitude near the injection septum is produced using three injection kickers. After injecting the beam, the electrons are accelerated to 450 MeV in nearly 200 ms following a linear ramp using the RF cavity operating at 31.619 MHz. Fields in the dipole, quadrupole and steering magnets are synchronously increased during the acceleration. The harmonic number of the ring is three giving rise to three circulating bunches in the ring. The accelerated beam is extracted by deflecting it by a fast kicker magnet having a rise time of 45 ns. As the separation between two bunches is 30 ns, during the extraction process, one out of three bunches is lost and two bunches are extracted. These two bunches are then transferred to Indus-1 through TL-2. The synchrotron operates at 1 Hz till the desired current is filled in Indus-1. The vacuum pressure in the synchrotron is better than 10^{-6} Torr.

The length of the transfer line-2 is about 25 m. The line has four quadrupole doublets and two dipole magnets to match the beam parameters at the injection point in Indus-1. One of the dipole magnets before Indus-1 will be kept off while transporting the 700 MeV beam from the synchrotron to Indus-2.

Subsystems

An accelerator can be classified into various subsystems such as magnets, magnet power supplies, RF system, beam diagnostics instrumentation, vacuum system, control system and low conductivity water plant, etc. All the subsystems and components have been designed at CAT. While most of them have been fabricated at CAT, a few of them have also been fabricated in other organizations including private industries.

Magnets: Various types of magnets are used in this facility. The dipole magnet of Indus-1 is 'C' shaped 90° sector type magnet[7,8]. It has a 35 mm mean pole gap with a magnetic field of 1.5 T and a field index of 0.5. Low

Table 3. Parameters of the synchrotron

Maximum energy	700 MeV*
Current	30 mA (11 mA achieved)
Circumference	28.45 m
Superperiods	6
Maximum dipole field	1.32 T
Tune point	2.25, 1.22
Momentum compaction	0.151
Revolution frequency	10.5 MHz
Harmonic number	3

*450 MeV for injecting into Indus-1.

carbon steel forged blocks are used for these magnets. Each magnet is made from two blocks. The machining of the pole gap is very critical because of small taper and also a very small pole gap. The field uniformity requirement of $\pm 5 \times 10^{-4}$ constrains the pole gap to be accurate to ± 40 μm. The flatness of machining surface has been achieved within 10 μm. The dipole magnets are energized by passing 800 A current through water cooled coils which are connected electrically in series and hydraulically in parallel. These coils are preformed in a hydraulic fixture in the required arc shape. The coils are wrapped with class H insulating tape for inturn insulation and epoxy potted for ground insulation. The quadrupole magnets were fabricated from cold rolled grain oriented (CRGO) Si steel sheets of 0.35 mm thickness and the sextupole magnets are fabricated from cold rolled non grain oriented (CRNGO) steel laminations of 0.5 mm thickness. The laminated construction was selected for better accuracy and is economical compared to solid magnets. The stampings were glued together in a high accuracy stacking fixture to get pole gap uniformity and then cured. The coils of the quadrupoles and sextupoles are water cooled.

In the synchrotron, the magnetic field is increased during ramping. The material for the magnets has been selected considering high permeability in the operating range, low coersive force, low remanent field and high saturation field. CRGO silicon steel of 0.35 mm thickness has been found to be suitable for both dipole and quadrupole magnets. To achieve a required field uniformity of $\pm 5 \times 10^{-4}$ over a good field region of 7 cm, pole gap uniformity of ± 50 μm was required to be maintained after assembly. The dipole magnet is 'C' shaped 60° sector type magnet with a mean radius of 1.8 m (refs 9, 10). The operating field of the magnet at the injection energy is 370 G, which increases to 1.3 T at 700 MeV. The magnet has been assembled using 24 small blocks and an entry and an exit block. These stampings are glued together using epoxy resin system and hardner. The stampings were assembled on a specially made fixture, which has got different small elements to control different parameters of the assembled block, such as pole gap, outer radius, inner radius and thickness of the block at different places. A laminated construction was used for quadrupoles. The stacking of stampings was done in a high accuracy fixture which maintains the perpendicularity in all the three mutually perpendicular directions in each quarter block. The water cooling coils of these magnets are made from oxygen-free high-conductivity copper conductors.

The dipole magnets were field mapped with a Hall probe. The Hall probe was mounted on a 2-axis CNC-controlled XY machine and was used for measurement of magnetic centre and magnet length. The multipole analysis of the quadrupole magnets was done by a rotating coil system.

The injection and extraction magnets are operated for a short time and their requirements are different. Septum magnets are made from 0.1 mm thick laminations of Ni–Fe alloy. The injection and extraction kicker magnets are fabricated using different types of indigenously developed ferrites. The magnetic field has to be highly uniform in the good field region and the higher order components should be as low as possible. These requirements demand an optimized design of the magnets.

Magnet power supplies: Regulated power supplies are required for the generation of the precise magnetic fields in dipole, quadrupole, sextupole, steering magnets and the septum and kicker magnets. Approximately 130 number of power supplies with ratings ranging from a few VA to about 1.0 MVA are used to energize the electromagnets for generation of magnetic fields[11]. The current stability requirement for the power supplies ranges from 1000 ppm to 100 ppm of current set. The schemes followed for power supplies are off line SMPS, linear series pass and SCR-controlled power supplies. Power supplies in the microtron, transfer lines and in the Indus-1 see passive R-L as load while the power supplies are ramped in the synchrotron. In the dipole and the quadrupole power supplies of the synchrotron, trapezoidal current passes through the main coils with a repetition rate of 1 Hz. Current is ramped from 20 Amp to 550 Amp in 200 ms, held there for 50 ms and forced to decrease faster thereafter so that injection for the next cycle is possible within a given time. All the power supplies have two basic control loops; a slow current loop and a fast voltage loop.

Pulsed power supplies required for the septum and kicker magnets are voltage-regulated. The currents in the power supplies of the septa and the injection kicker magnets are sine waves of half periods of a few tens of microseconds with peak currents of a few hundred amperes repeating with the repetition rate of the system (1 Hz at present). The extraction power supply of the synchrotron follows a half sine wave with a rise time of 45 ns and a flat time of nearly 100 ns during which the bunches are extracted. The injection kicker of Indus-1 has a sine wave shape during rise of a pulse of 1 μs and an exponential fall time of 150 ns during which the bunches are injected. These power supplies have a very small time jitter.

Radio frequency cavities: Two RF cavities having an operating frequency of 31.613 MHz are used, one for the synchrotron and the other for the storage ring Indus-1 (ref. 12). The available length in the straight sections for the RF cavities is 80 cm in the synchrotron and in Indus-1. Because of this and the relatively lower frequency of operation, a capacitively loaded structure was chosen for the RF cavities. In the synchrotron, energy gain per turn is 0.8 keV and the synchrotron radiation

loss at 700 MeV is 11.8 keV. This leads to a total beam power of 378 W. The peak voltage to be generated across the cavity is 30 kV. In Indus-1, the synchrotron radiation loss is 3.63 keV/turn, which requires 363 W of beam power. To provide sufficiently high overvoltage factor (peak RF voltage/energy loss per turn) to achieve sufficient beam lifetime, the peak cavity voltage is kept at 30 kV. The power needed to generate 30 kV is 2.5 kW. The amplifier is tested up to 8 kW. In the RF system, the signal from an oven controlled crystal oscillator, which has a frequency stability of 10^{-8} is fed to a preamplifier and then to the phase shifter. This signal is then fed to the programmable attenuator, which controls the driving power to the 200 W solid state driver amplifier which drives the main power amplifier. Both the amplifiers have been built using indigenous components. The power from the amplifier is transmitted through a flexible coaxial cable. This cable is joined to the cavity input coupler through a tapered transition. The input coupler consists of a section of coaxial line, a disk type ceramic window and the coupling loop.

The signal necessary in the amplitude, phase and frequency control loops is obtained from the sensing coupler. The signal sensed through the sensing loop is fed to the frequency and amplitude control loops. In the case of frequency control, the phase of this signal is compared with that of another signal from the cavity input coupler and the error signal thus obtained is given to the error amplifier and the logic generator circuit which drives the tuning plunger to restore the cavity frequency. In order to control the gap voltage, the signal from the sensing coupler is fed to the amplitude control circuit which compares level of this signal with the external amplitude set signal. The error signal thus obtained is fed to a programmable attenuator, which controls the driving power to the 200 W amplifier, which in turn drives the power amplifier and the cavity voltage.

The RF cavity of the microtron has an operating frequency of 2856 MHz. The microwave system of the microtron consists of microwave source, transmission line and RF cavity. A 5 MW pulsed klystron tube is used along with a driver klystron and a solid state synthesizer. The RF cavity is a cylindrical cavity resonant in TM010 mode, having apertures in the end walls to focus and allow passage of the electrons.

Vacuum system: The vacuum system has been designed to maintain a pressure of less than 10^{-9} Torr in Indus-1 with full load and 10^{-7} Torr in the synchrotron, transfer lines and the microtron[13]. Turbo molecular, sputter ion and Titanium sublimation pumps are used at different stages. Stainless steel has been chosen as the material for the vacuum chambers. Flange joints with copper gaskets are used for interconnection of chambers. The chambers and components forming part of the ultra high vacuum (UHV) envelope are preconditioned by ultrasonic,

alkaline and acidic cleaning, electropolishing followed by high temperature vacuum degassing and argon discharge cleaning. Vacuum chambers for the dipole sections of the Indus-1 have a box-type design with two tangential ports, one for tapping synchrotron radiation and the other for a distributed ion pump. The chambers for the straight sections of Indus-1 have been fabricated using SS tubes. Ion clearing electrodes are mounted at a few locations in the straight sections to mitigate the ion trapping problem.

For the synchrotron, to minimize distortion in the magnetic field due to eddy currents during ramping, thin wall SS bellow type chambers, with a wall thickness of 0.3 mm, have been specially designed. There was no need to construct a chamber for a microtron. In this case, employing a suitable construction of the magnet poles forms the beam chamber.

Penning gauges and Bayard and Alpert (BA) gauges are used for measurement of the pressures, whereas residual gas analyser and compact helium leak detector cells are mounted at some locations for monitoring the composition of residual gases and for leak hunting respectively during operation of the accelerators.

Beam diagnostics: Various beam diagnostic devices are required during commissioning and routine operation of these accelerators[14]. The parameters that one would like to measure and observe are: beam current, beam position, beam profile, beam emittance, bunch length, etc. Fluorescence screens are used at various locations in the transfer lines to monitor the beam path and spot size. These are used to observe first turn circulation in the synchrotron and the storage ring. Fast current transformers (FCT), DC current transformers (DCCT), wall current pickups (WCP) are used for current monitoring at various stages of the accelerators. A number of beam position indicators (BPI) are used in the synchrotron and Indus-1 for monitoring the closed orbit distortion of the beam. These monitors have a wide band signal processing electronics, a data acquisition and display system. A Radio Frequency Knock Out (RFKO) system is used in the synchrotron and Indus-1 for measuring the betatron frequencies (tunes). In the synchrotron light monitoring station, the visible part of the synchrotron radiation is reflected using a metal mirror and the profile of the electron beam can be obtained with the help of solid state imaging arrays. Using part of this radiation, bunch length can be measured using an image dissector tube.

Control system: The design of the control system for the Indus-1 facility is based on a modular and distributed architecture[15]. The control system is a distributed processor network comprising personal computers serving as intelligent workstations and a number of microprocessor-based device controllers dedicated to the task of data acquisition, monitoring and control. Each device controller has an autonomous capability to control the subsystem to which it is connected. The control system is distributed hardwarewise over three layers. At the bottom is the front end instrumentation which conditions the output from an equipment directly connected to the machine, into standard electrical signals. The front end instrumentation is connected upward to intelligent Supervisory Control and Data Acquisition System (SCADA). The output from these controllers is connected to a workstation situated in the main control room.

The operation of the control system is divided into two major tasks: (i) Informing the operator about various aspects of the operation of the accelerator. These are the values of various parameters such as magnet currents, vacuum pressures, temperatures, frequency, voltages, currents, power, beam positions, time delays, radiation levels, status of interlocks, status of pumps, etc. (ii) Conveying the messages and commands issued by the operator to the concerned devices.

The hardware of the control system is based on a 16 bit microprocessor; Motorola 68000 family is chosen as the standard. The hardware is modular based on VME bus. The SCADA crate consists of a master processor board based on the 68000 microprocessor and the necessary input/output modules. I/O modules handle a variety of analog and digital signals.

Cooling system: Accelerator cooling demands low conductivity cooling water since water runs parallel to current carrying conductors. The cooling water is common to systems where different electrical environments exist and corrosion and scaling should be avoided in cooling channels.

A low conductivity water (LCW) plant was set-up for Indus-1. The plant consists of three water circulation loops, viz. DM loop, primary loop and secondary loop. DM loop involves demineralization of make up water using DM columns of cation, degasser, anion and mixed bed columns. Water, with its ions stripped off to an extent of 1 micro-seimen conductivity is stored in storage tanks for circulation. DM loop is an off-line loop, operated whenever initial filling or make up water is required. Primary loop circulates LCW through an array of parallel pumps to various subsystems to be cooled. Every individual cooling line is fitted with flow switch at return path, which is used to switch off the system if the water flow is not sufficient. Return hot water is passed through a heat exchanger exchanging heat with the secondary water. Water, thus cooled returns to the storage tank. Storage tank is padded with 10 psi nitrogen to decrease dissolved oxygen concentration in circulating water. Primary loop is a closed loop. Primary pipe line is of SS to avoid contamination to cooling water. Secondary loop is required to extract heat from the primary loop. This consists a cooling tower, from the basin of which water is sucked and circulated through heat exchanger to

remove heat from primary water. Hot water returning from heat exchanger is fed to a cooling tower for further cooling. Secondary circulation is by soft water, generated by a stand alone softener.

Indus-1 LCW plant is designed and installed as a manually operated plant. A few of the operations are made automatic to facilitate smooth operation. Indications like temperature, pressure and flow in different loops are continuously monitored. Water flow is interlocked with the respective power supplies for safety.

Commissioning

The microtron was commissioned towards the end of 1994. Since then it is regularly delivering a 20 MeV beam of pulse current 25 mA, pulse length of ~ 1 µs at a repetition rate of 1 Hz. TL-1 optics has also been optimized for this microtron beam and TL-1 is being used regularly for transfer of electrons from the microtron to the synchrotron. Beam emittance of the microtron beam was measured in TL-1 (ref. 16).

Initially, the synchrotron was operated at the injection energy to carry out some measurements. As the currents in the magnets were increased, the beam was successfully accelerated to 480 MeV with nearly 2 mA accelerated beam current. In subsequent operations, the accelerated beam current was increased to ~ 11 mA mainly due to the correction of orbit using the horizontal and vertical steering magnets, ramping of the RF voltage from 1.5 to 6.0 kV and possibly due to improvement in the field pattern of dipole magnets. The RF cavity was detuned by ~ 5 kHz with respect to the generator frequency of 31.616 MHz to overcome the Robinson instability driven by the fundamental accelerating mode.

To understand the behaviour of the beam during ramping, beam dynamical parameters such as betatron tunes, chromaticities, beta functions, bunch length, dispersion function, closed orbit distortion were measured[17].
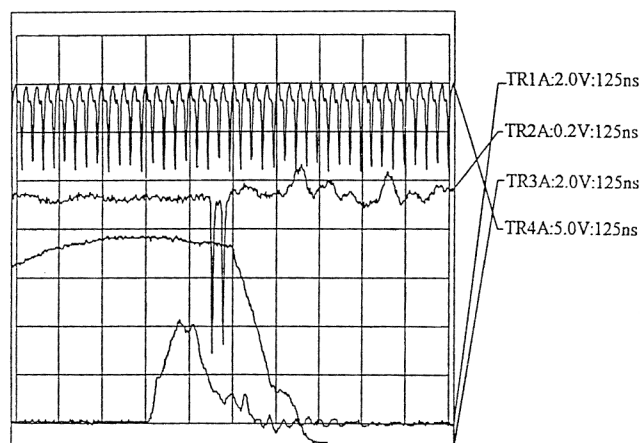
To extract the beam from the synchrotron, the extraction kicker was energized to give a kick of ~ − 10 mrad which makes the closed orbit displacement of ~ 36 mm at the extraction septum location. The kicked beam was observed on the mouth of the extraction septum magnet painted with fluorescence material. The two extracted bunches were monitored in TL-2 using a WCP. By optimizing the currents in the quadrupoles and steering magnets in TL-2, the beam was transported up to injection point of Indus-1. The extraction kicker is synchronized with the dipole extraction current to ensure the fixed energy of the extracted beam.

A bright beam spot was observed on the injection septum mouth. By adjusting the steering magnets at the end of TL-2, the beam spot was passed through the centre of the septum magnet. Currents of the septum magnet, dipole and quadrupoles of Indus-1 were optimized to circulate the beam without the injection kicker and with RF cavity off. A beam spot was observed on the fluorescence monitor placed in S2 and maximum six turns were observed in the WCP placed in S3.

The real task of beam injection trials to Indus-1 began in April 1999 immediately after the installation of the injection kicker magnet into the ring. Initially by operating the kicker at 1700 A, beam circulation up to 30 turns was observed without RF. On optimization of the kicker field and strengths of the quadrupoles during subsequent operations in the presence of RF, beam storage began to take place but the beam accumulation (an increase of beam current in Indus-1 with the incoming bunches of electron beam from booster synchrotron) was still not taking place smoothly. With optimization of kicker current, the stored beam could survive during the injection process. Figure 6 shows the accumulated current (TR4A) along with the injected beam at the end of TL-2 (TR2A), the injection kicker pulse (TR3A) and the synchrotron extraction kicker pulse (TR1A).

The beam lifetime was initially poor due to the degradation of vacuum caused by the cleaning of the vacuum

TR1A:2.0V:125ns

TR2A:0.2V:125ns

TR3A:2.0V:125ns

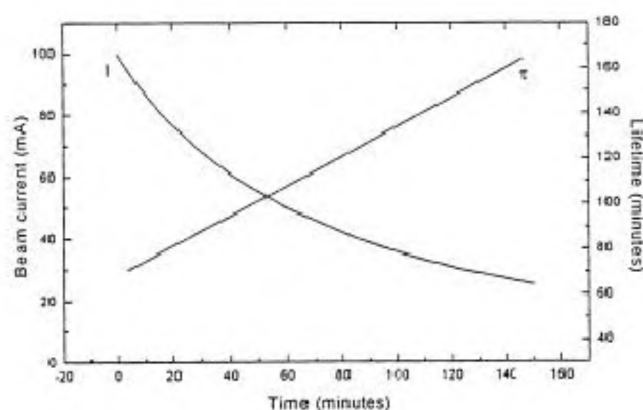TR4A:5.0V:125ns

Figure 6. Beam accumulation in Indus-1.

Figure 7. Decay of current in Indus-1.

chamber by synchrotron radiation. As the vacuum improved, the beam lifetime (time to reduce the current to $1/e$th of its value) at 100 mA improved to nearly 75 min at an average pressure of 10 nTorr. The beam lifetime in this case appeared to be governed by the vacuum. The beam lifetime will further improve as the vacuum pressure approaches 1 nT as required at the beam current of 100 mA. The decay of the current as shown by the DCCT and the beam lifetime at different currents is shown in Figure 7.

The measurements of beam dynamical parameters like betatron tune, beta functions, chromaticities, dispersion function, bunch length, closed orbit distortion, etc. have been carried out at the tune point (1.69, 1.31) at which the maximum current has been achieved[18].

Conclusions

The Indus-1 SR facility was commissioned in early 1999 with maximum accumulated current of 161 mA. The accumulated current increased up to 200 mA in March 2001. The injector system commissioned earlier has been working satisfactorily. The beam dynamics experiments carried out on the synchrotron and the storage ring beam show that the measured parameters closely match the design parameters. At present, the lifetime in the storage ring appears to be limited mainly due to the vacuum. With regular operation of the storage ring for a few hours daily, the vacuum will improve further and consequently lifetime will also improve.

1. Bhawalkar, D. D. *et al.*, Proceedings of International Symposium on Medium Energy Synchrotron Radiation Facilities in Asia, World Scientific, Singapore, 1990, p. 16.
2. Ramamurthi, S. S., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 9.
3. Singh, G., Sahoo, G. K., Singh, B., Angal Deepa and Ramamurthi, S. S., Proceedings of the Symposium. on Synchrotron Radiation Applications, Hefei, China, 1989, p. 122.
4. Soni, H. C. and Ramamurthi, S. S., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 181.
5. Angal Deepa, Singh, G. and Ramamurthi, S. S., *Indian J. Phys.*, 1991, **65** A(6), p. 501.
6. Singh, G., Sahoo, G. K., Angal Deepa, Singh, B., Ghodke, A. D. and Ramamurthi, S. S., CAT Report No. 88/CAT/EAP/30000/0001/D, 1988.
7. Mhaskar, S. P., Mishra, R. K. and Tomar, V., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 210.
8. Prabhu, S. S., Puntambekar, A. M., Singh, J., Veerbhadhriah, T., Shreevastava, V. K. and Ramamurthi, S. S., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 216.
9. Mishra, R. K., Mhaskar, S. P., Shinde, R. S., Shiv Kotaiah, Murthy, Y. R. C. and Tomar, V., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 213.
10. Prabhu, S. S., Puntambekar, A. M., Hussain, K. A., Sreeramalu, K. and Ramamurthi, S. S., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 220.
11. Tiwari, S. R., Thakurta, A., Thipsay, A. P., Pagare, A., Gandhi, M. L., Singh, T. N., Singh, S. and Kotaiah, S., Proceedings of the First Asian Particle Accelerator Conference (APAC-98), KEK, Tsukuba, Japan, 1998.
12. Pande, S. A., Lad, M., Chaudhary, S. S., Hannurkar, P. R. and Ramamurthi, S. S., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 232.
13. Ramamurthi, S. S., Karmarkar, M. G. and Patel, R. J., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 252.
14. Banerji, A., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 245.
15. Vaidya, B. J., Adhikari, J. S., Shukla, D. N., Fatnani, P. and Barpande, K., Proceedings of International Conference on Synchrotron Radiation Sources, Indore, 1992, p. 259.
16. Angal-Kalinin, D. and Singh, G., *Indian J. Pure and Appl. Phys.*, 2000, **38**, 296.
17. Sahoo, G. K. *et al.*, Proceedings of the First Asian Particle Accelerator Conference (APAC-98), KEK, Japan, 1998.
18. Sahoo, G. K. *et al.*, Paper presented at European Particle Accelerator Conference, Vienna, June 2000.