Beamlines on Indian synchrotron radiation source Indus-1

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In India, at the Center for Advanced Technology (CAT), Indore a 450 MeV electron synchrotron radiation source Indus-1 has been commissioned. This source gives synchrotron radiation from soft X-rays, vacuum ultra violet (VUV) rays to infrared. To use this radiation from Indus-1 for different experiments, six beamlines and experimental stations are planned. Of these six beamlines, two are now operational and the rest are under commissioning. We give here a brief description of characteristics of Indus-1 source, and the description of the various beamlines and their current status.

SYNCHROTRON radiation (SR) has emerged as a tool for basic and applied research in physics, chemistry, biology, medicine and industry, because of its unique characteristics, namely broad spectrum (from far-infrared to X-rays), small beam size and small divergence and hence high brightness, short pulse duration and high degree of polarization.

It is well known that whenever a charged particle is accelerated, it emits electromagnetic radiation. The acceleration can result in a change of speed or a change in the direction of motion of the charged particles. Thus, to generate SR, a charged particle is forced to move in a curved path under the action of a magnetic field; the particle experiences centripetal acceleration and hence emits radiation.

The wavelength and intensity of the emitted radiation depend upon the strength of the magnetic field, and the mass, charge and energy of the charged particle. The loss of energy in the form of SR is very severe for lighter particles. For this reason, electrons are mostly used to generate SR.

The energy loss per turn per electron is given by

$$\Delta E(\text{keV}) = 88.5E^4(\text{GeV})/R(\text{m}), \quad (1)$$

where E is the electron energy and R is the radius of curvature. The power radiated by a relativistic electron is

$$P(\text{kW}) = 22.6E^3(\text{GeV})\ B(\text{T})I(\text{A}), \quad (2)$$

where B is the bending magnetic field and I is the current.

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The properties which are associated with SR can be obtained by visualizing the electron as an oscillating dipole subjected to Lorentz transformation and then applying the laws of classical electrodynamics to the motion of electrons. These properties are (a) broad spectrum (from infrared to optical to vacuum ultraviolet, soft X-rays and X-rays), (b) high intensity and high brilliance, (c) high degree of collimation, (d) high degree of polarization, and (e) pulsed time structure.

The critical wavelength, λ_c the wavelength above and below which the total radiated power is divided equally, also depends upon E and B through

$$\lambda_c(\text{Å}) = 18.64/(E^2(\text{GeV})B(\text{T})). \quad (3)$$

Synchrotron radiation sources have many applications both in basic sciences as well as in industries. The fields of research in which SR plays a dominant role can be categorized into (a) condensed matter physics, (b) surface science, (c) atomic and molecular physics and chemistry, (d) life sciences, and (e) industrial applications.

Condensed matter studies encompass physics, chemistry and materials science. These involve chemical compositional studies, structural studies and electronic structure studies. For chemical composition or elemental analysis, techniques like photoelectron spectroscopy to measure electronic core level binding energies, X-ray absorption spectroscopy and X-ray fluorescence spectroscopy are employed. New generation of high brilliance sources together with their time structure and analysis techniques would provide new and unique possibilities of studies involving dynamics such as diffusion and inter diffusion in interfaces.

The study of crystal architecture is always exciting and techniques like neutron diffraction and conventional X-ray diffraction are available. However, the unique properties associated with SR have not only strengthened this area but also opened new areas which were hitherto not possible. For example, high brightness helps in getting data sets which are much more extensive than those obtained with a laboratory X-ray or vacuum ultra violet source. Due to high degree of collimation, difference Fourier techniques are now feasible to isolate effects of atoms in non-stoichiometric materials. Study of crystals under ultra high pressure using diamond anvils has opened up a new area with high brilliance sources.

Table 1. Parameters of Indus-1

	Designed	Achieved
Electron energy	450 MeV	450 MeV
Beam current	100 mA	170 mA
Beam lifetime	1.8 h	1.0 h at 100 mA
Dipole bending field	1.5 T	
Critical wavelength (energy)	61.38 Å (202 eV)	
Circumference	18.96 m	
Photon flux (at λ_c)	7.2×10^{11} photons/s/mrad horiz./0.1% BW	
Brightness	6.5×10^{11} photons/s/mm^2/mrad^2/0.1% BW	
Bunch length	113 mm	
Revolution frequency	15.82 MHz	
Harmonic number	2	

For electronic structure of solids, angle-resolved photoelectron spectroscopy, EXAFS, XANES, etc. are some techniques which are used using SR. Magnetic X-ray absorption and scattering were so far only considered theoretically, as the cross-section for such scattering is very small. Now due to the availability of high brightness sources, magnetic scattering studies are possible. Magnetic circular dichroism is a technique which uses circularly polarized light of opposite helicity from SR to find the spin and orbital magnetic moments in a material. Another technique which was not possible earlier is X-ray Raman effect due to its weak nature.

The study of surfaces is gaining interest because properties of the surfaces are determined by one or two monolayers of the atoms. Here also SR is playing an important role. The study of heterogeneous catalysis atomic structure of surfaces, surface electronic structure are some of the areas where techniques like X-ray diffraction, small angle scattering, EXAFS, etc. are employed.

In life sciences, study of biological systems to understand the intricate relationship between the structure of the system and its biological activity is a fascinating subject. Imaging of biological molecules, protein crystallography, structural studies of active site of enzymes, study of fibre and self-assembly, membrane system, etc. are a few examples. These experiments have now gained momentum and study of this will lead to modern drug design.

One major industrial application of synchrotron radiation is in lithography. Lithography is a technique used in the production of highly integrated silicon- based circuits with the smallest possible dimensions. This technique is also used in micro machining.

The list of applications of SR given above indicates only some major applications and the list is not exhaustive.

There are not many countries in the world where dedicated accelerators have been built to generate and use SR. In India, such a synchrotron source is being built at our Center. In the first phase, the energy of electrons in the storage ring (where electrons circulate with a definite energy and current) is 450 MeV. This is named as Indus-1. In the second phase (named Indus-2), the energy of electrons in the storage ring will be 2.5 GeV whereby a good photon flux in the wavelength less than 1 Å will be available.

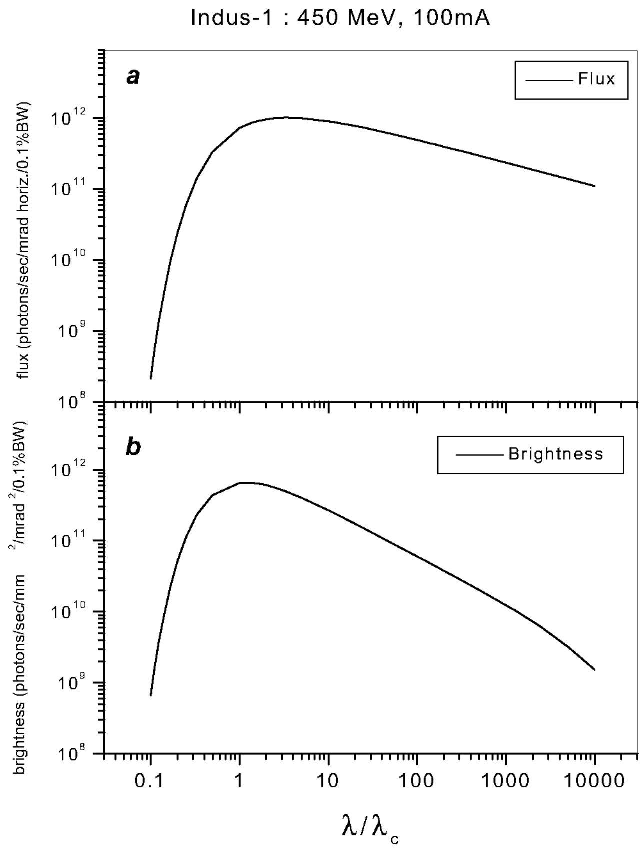

Figure 1. ***a***, Photon flux and ***b***, spectral brightness from Indus-1 at 100 mA electron beam current.

Characteristics of Indus-1

Indus-1 became operational in 1999. The stored electron beam current of ~ 200 mA has been achieved though the lifetime at this current is rather small. The designed value of ~ 100 mA and one hour lifetime is achieved at this current as against 1.8 h. This lifetime will increase after continuous operation of the beam due to 'beam cleaning of the vacuum chambers', thereby reducing the outgassing rate due to photon-induced desorption of walls of the vacuum chambers. Details of the Indus-1 source are given in a separate article in this issue[1].

The main characteristics of Indus-1 are given in Table 1. Figure 1 *a* and *b* represents flux and brightness of the photons from Indus-1 storage ring. As mentioned earlier, the critical wavelength in Indus-1 is 61 Å.

Indus-1 beamlines

Indus-1 storage ring has four bending magnets with a radius of 1 m. Beamlines are drawn only from three bending magnets as the fourth one is close to the injector septum and transport line from the booster synchrotron. The beamlines which can be tapped from these three bending magnets are shown in Figure 2. Each dipole magnet vacuum chamber has two ports, one at 10° and the other at 50°. From each port two beamlines can be tapped. Due to various constraints, six beamlines are possible from these bending magnets.

Before discussing Indus-1 beamlines in particular, it is worthwhile to know what does a beamline mean. A beamline is generally the instrumentation that is used between the synchrotron source and the target where the beam will hit. A schematic diagram of the beamline is shown in Figure 3. It consists of SR source, a front-end, beam transport optics and experimental station followed by data acquisition system.

The source usually refers to the type of synchrotron radiation source from where SR is emanating. For example, the source could be a bending magnet, or a wiggler or an undulator. The source is generally characterized by its emittance. It is an important quantity required while designing a beamline for any experiment. In Indus-1 we are using only bending magnet sources.

Front-end is a device which protects the ultra high vacuum of the ring from any vacuum breakdown in the beamline or in the experimental station. Indus-1 being a soft X-ray, vacuum ultra violet ring, it is necessary to expose beamline directly to the ring. Indus-1 front-end consists of a fast closing shutter and a pneumatic ultra high vacuum gate valve. A vacuum sensor is kept on the experimental side of the chamber. Any deterioration in the vacuum would give a signal to the fast acting shutter which will be closed in 10 ms followed by pneumatic gate valve which will be closed in one second. Thus, the vacuum in the storage ring is protected. Schematic diagram of the Indus-1 front-end is shown in Figure 4.

The beam transport channel for any beamline consists of a pre-mirror to focus incident radiation, a monochromator, and a post-mirror to focus monochromatic beam onto the target. The choice of optical elements and their configuration vary from beamline to beamline depending upon the need of an experiment, e.g. high spectral resolution or high intensity. To achieve the desired specifications of a beamline a monochromator plays an important role.

In the following we will describe the salient features of various beamlines and the experimental stations, as well as their status.

Reflectivity beamline

The reflectivity beamline is designed taking 10 mrad and 5 mrad as horizontal and vertical divergences of the beam from a bending magnet of Indus-1. The pre-mirror is a toroidal mirror to focus the SR beam onto the entrance slit of the monochromator with a vertical deflection. The

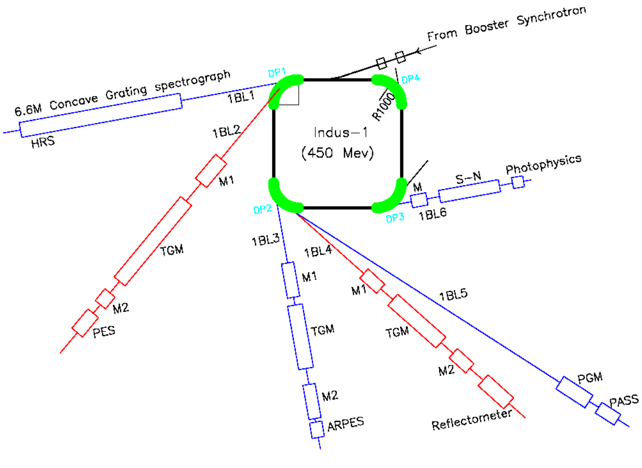

Figure 2. Layout of the experimental hall, bending magnets and positions of beamlines. DP1 . . . DP4 are the bending magnet chambers; 1BL1 . . . 1BL6 are the beamlines; HRS, high-resolution spectroscopy beamline; PES, photoelectron spectroscopy beamline; ARPES, angle resolved photoelectron spectroscopy beamline; PASS, photon absorption spectroscopy station; TGM, toroidal grating monochomator; PGM, plane grating monochomator; S-N, Seya-Namioka monochomator; M1 and M2 are the pre- and post-focusing mirrors.

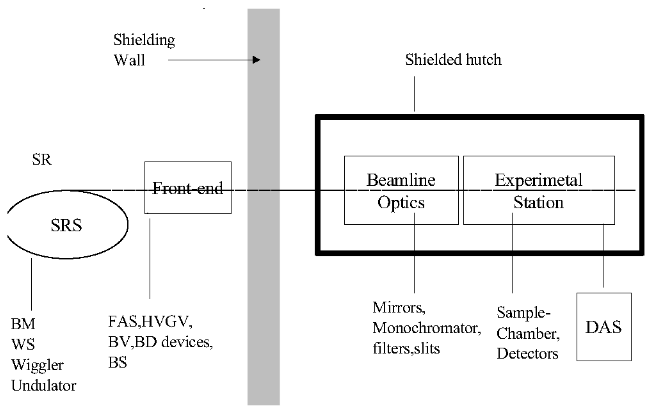

Figure 3. A schematic diagram of a beamline from a synchrotron radiation source, BM, bending magnet; WS, wavelength shifter; HVGV, high vacuum gate valve; BD, beam diagnostic.

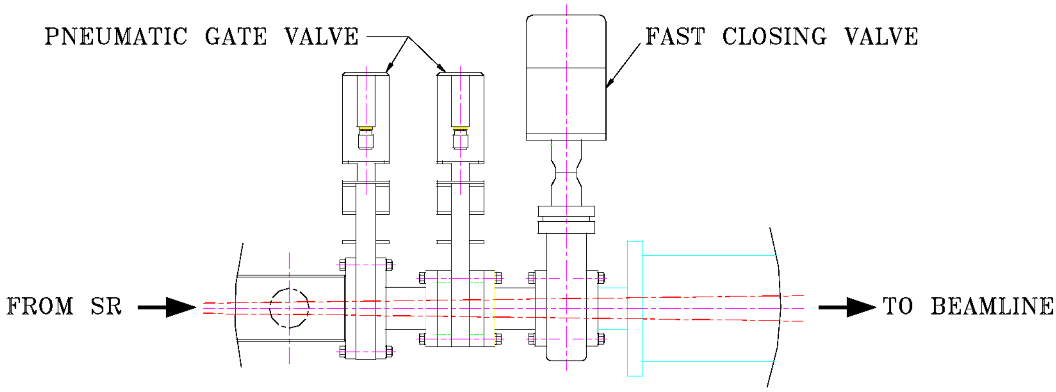

Figure 4. Schematic diagram of Indus-1 front-end.

beam is incident at 4.5° to the mirror surface. This mirror is gold-coated and has a demagnification ratio of 2 : 1.

The monochromator used is a toroidal grating type. The entrance slit of the monochromator can be changed in the horizontal from 0.4 mm to 3 mm in four discrete steps, whereas the vertical slit is adjustable from 1 to 1.8 mm. The deflection angle at the grating is 162°. The gratings are holographically etched and can be interchanged in ultra high vacuum. There are three gold-coated gratings with 1800, 600 and 200 lines/mm to cover the wavelength range from 40 Å to 1000 Å. The spectral resolution is estimated to be good. The post-mirror is also a toroidal type to refocus the monochromatic beam onto the target, which is located at a distance of 1.8 m from the center of this mirror. The demagnification ratio is 1 : 1. The typical spot size is 1 mm (H) × 1 mm (V). The expected photon flux is 10^{11} ph/s. The beamline and the experimental station are shown in Figure 5 *a* and *b* respectively. Details of the beamline are given in ref. 2. The beamline is under ultra high vacuum which is obtained by a combination of turbomolecular pumps and sputter ion pumps.

The experimental station is a multipurpose reflectometer[3]. It operates in vacuum of 1×10^{-8} mbar and has a two-axis goniometer with independent and coupled rotation of sample and detector with high angular resolution of 2.5-milli degree. Between the beamline and the reflectometer a differential pumping station is installed as the beamline is under vacuum of 10^{-9} mbar. It is possible to set the reflectometer in either s or p polarization geometry. The detectors which are used are either Si or GaAsP photodiodes. The station is computer controlled. Typical experiments, which can be performed on this beamline, are the measurement of VUV reflectivity of thin films and multilayers, optical constant determination, and measurements of reflectivities and efficiencies of SR gratings. The chamber has a flexibility to suit different experimental requirements. Details of the beamline and some commissioning results are given in a separate article in this issue[4]. The maximum measured photon flux is in the range of 10^{11} ph/s while the measured resolution $\lambda/\Delta\lambda$ is 500.

Figure 5. ***a***, Beamline and ***b***, reflectometer.

Angle integrated photoelectron spectroscopy beamline

This is a toroidal grating monochromator-based beamline with pre-mirrors as pre- and post-focusing optics. The horizontal and vertical divergences of the beam are 10 mrad and 4 mrad respectively. The focal length of the toroidal grating is 2600 mm with deflection angle 162°. The sample is located at a distance of 1 m from the post-mirror which is platinum-coated. The demagnification ratio is 1 : 1. The monochromator has three interchangeable gratings with 200, 600 and 1800 lines/mm to cover the wavelength range from 60 to 1250 Å. The expected resolution $\lambda/\Delta\lambda$ is 500.

The experimental station on this beamline is an angle-integrated photoelectron spectrometer built indigenously. This is an ultra high vacuum compatible spectrometer comprising 100 mm main radius hemispherical analyser and a channeltron detector. The chamber is equipped with a twin anode X-ray source (AlK_α & MgK_α lines), sample manipulator with X-Y-Z motors, sample heating (up to 900°C) and cooling (liquid N2) facilities. The sample preparation chamber has a diamond file for sample scrubbing attachment and quick load lock system with magnetically coupled transfer rod. The calculated energy resolution of electron energy analyser is 800 meV. Optical layout is shown in Figure 6. Details of the beamline are given in an article in this issue[5].

The angle-integrated photoelectron spectroscopy beamline can be used to obtain information on electron density of states, band structure of bulk materials, and surface physics. This beamline and the experimental station are commissioned and are now being used.

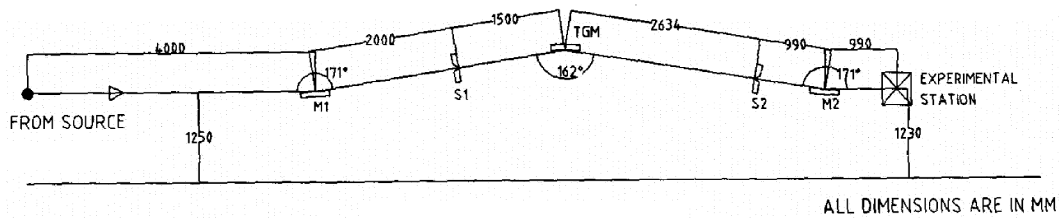

Figure 6. Optical layout of the angle integrated photoelectron spectroscopy beamline. M_1 and M_2, pre- and post-mirrors; TGM, toroidal grating monochromator; S_1 and S_2, entrance and exit slits (after ref. 5).

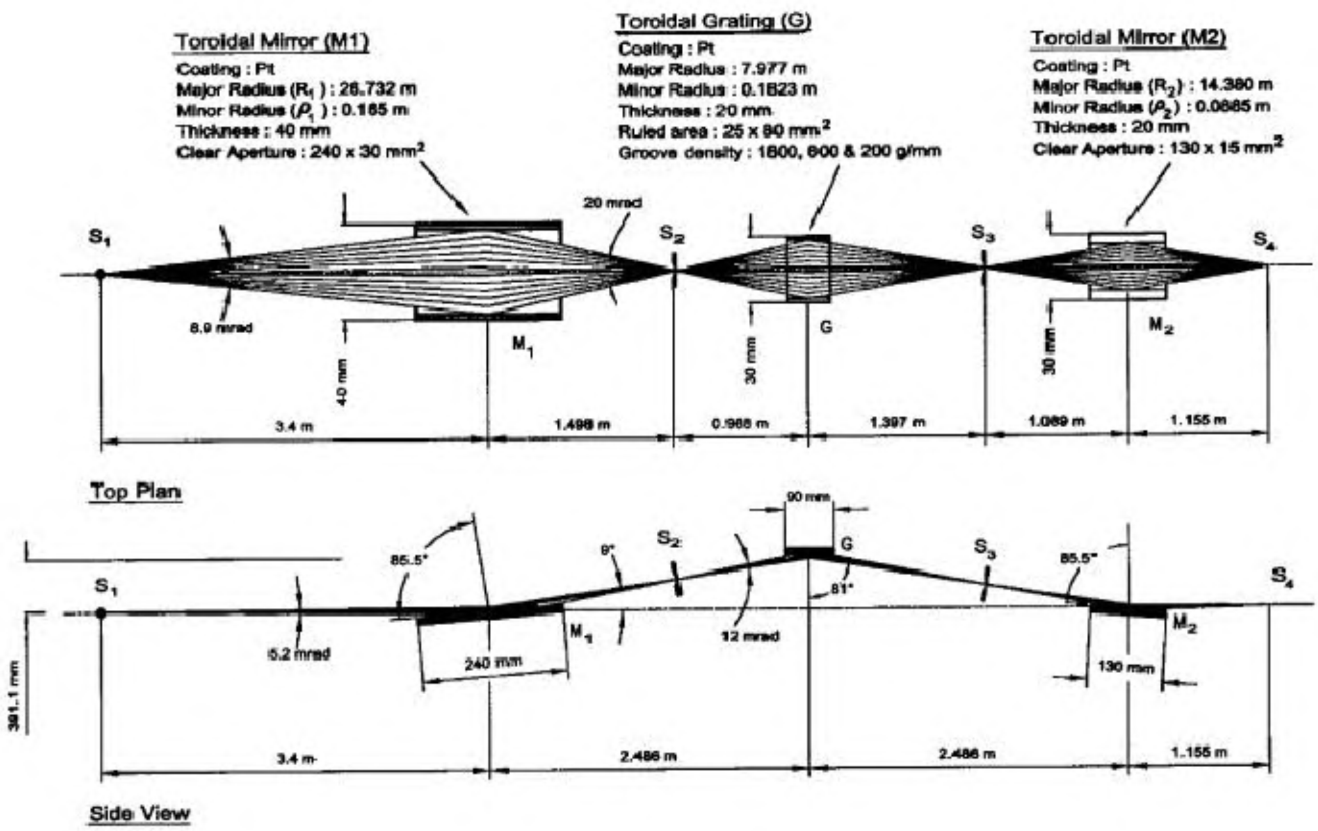

Figure 7. Optical layout of the angle resolved photoelectron spectroscopy beamline (after ref. 6).

Angle resolved photoelectron spectroscopy beamline

This beamline has toroidal mirrors as pre- and post-optics. The monochromator is also a toroidal grating type. Horizontal and vertical acceptances are 9 and 5 mrad respectively. Mirrors and gratings are coated with platinum.

Photon flux expected at the sample is 10^{10} ph/s. The monochromator covers the wavelength range from 40 to 1000 Å.

The experimental station is an ultra high vacuum chamber housing an angle integrated as well as angle resolved electron analyser. It has a low energy electron diffractometer (LEED), Auger probe for orientation of single crystal, a sample manipulator, an argon ion sputter etch gun for *in situ* sample cleaning and detection. Ultra high vacuum 10^{-10} mbar is obtained by a combination of a turbo molecular pump, sputter ion pump and a titanium sublimation pump. The energy resolution of the electron energy analyser is 50–100 meV. Optical layout is given in Figure 7 (ref. 6).

The beamline is undergoing commissioning and is expected to be ready by the latter part of the year 2001.

Photo physics beamline

This beamline is to cover a wavelength range of 500–2500 Å using a 2400 l/mm gold-coated grating with a spectral resolution of 1000. It accepts 41 mrad horizontal and 5.6 mrad vertical radiation. The pre-mirror, toroidal in nature focuses the SR beam on the entrance slit of a 1 m Seya-Namioka monochromator using a spherical grating. The entrance and exit slit are variable from 0 to 2 mm and 0 to 1 mm in the horizontal and vertical plane respectively. The typical spot size is around 1 mm × 1 mm and the expected photon flux is 10^{10} ph/s on the target. Optical layout is given in Figure 8 (ref. 6).

The experimental station consists of a ¼ meter UHV cell for absorption and emission spectroscopy experiments in gas phase and an UHV chamber and sample holder for solid samples.

The beamline is being assembled and is expected to be ready soon.

High resolution spectroscopy beamline

This beamline is to perform high-resolution spectroscopy work in the wavelength range 400–2500 Å with a spectral

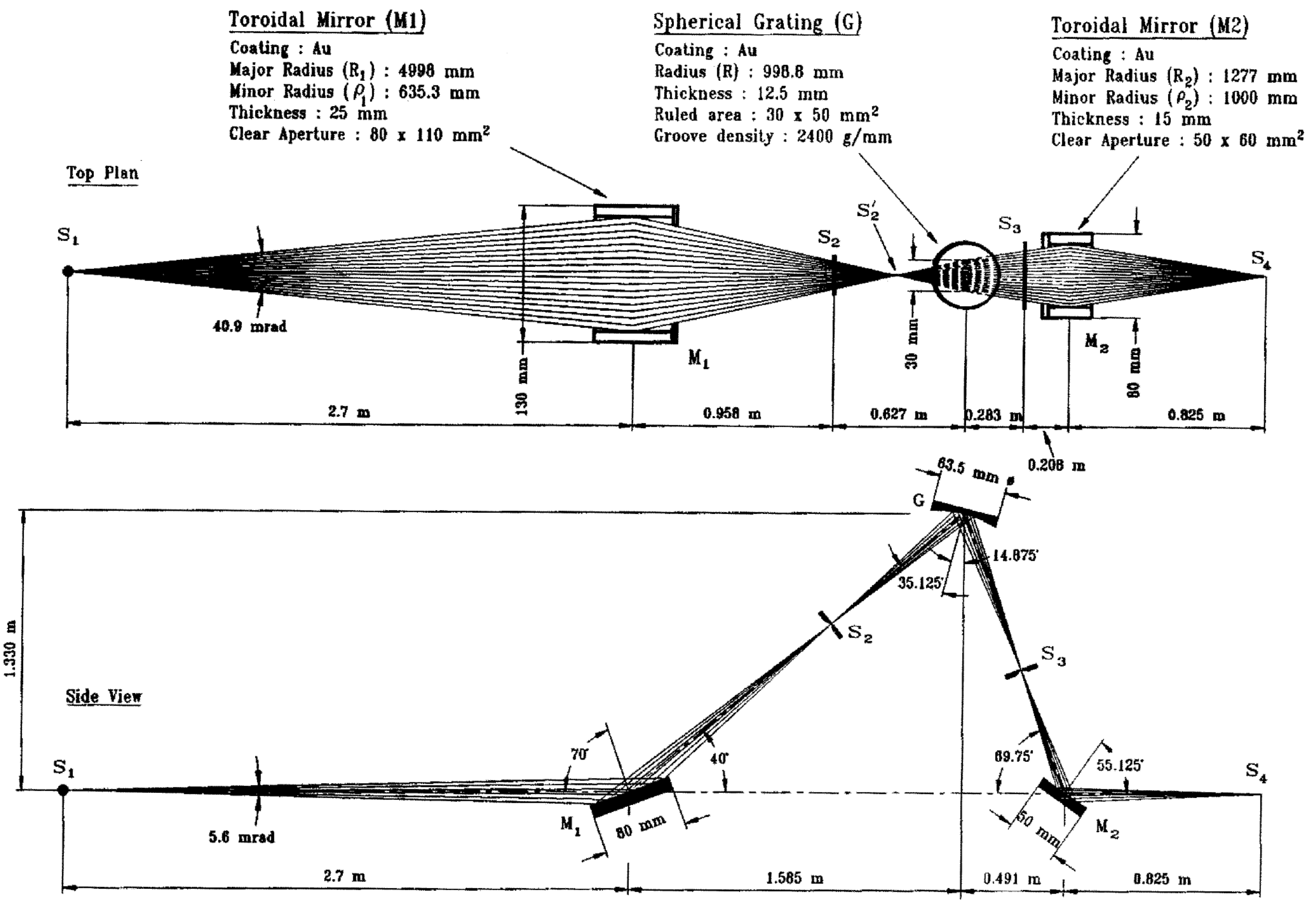

Figure 8. Optical layout of the photo physics beamline (after ref. 6).

resolution of 10^5. The acceptance of the beamline from the bending magnet is 60 mrad horizontal and 6 mrad vertical. A combination of three cylindrical mirrors focuses the SR beam onto the entrance slit of a 6.65 m spectrometer in off plane-eagle mount having gold-coated concave grating of 4800 lines/mm. The beamline is expected to be ready by 2002.

Photon absorption spectroscopy beamline

This beamline is planned on a plane grating monochromator to perform photon absorption experiments in the wavelength range 20–1200 Å. The resolution $\lambda/\Delta\lambda$ aimed at is ~ 1000. This beamline is expected to be ready by 2002.

Other facilities

In addition to beamlines, there are other facilities available for users to do off-line experiments. These include a 200 keV transmission electron microscope with X-ray analysis facility, a scanning electron microscope, sample preparation facilities like an UHV electron beam evaporation system, furnaces, dark room, X-ray fluorescence facility, etc. Other peripheral facilities like computation, library, workshop, chemical-treatment plant, glass blowing section, etc. are also available.

Summary

The article gives a brief account of Indus-1 and beamlines, which are working and will be working in the near future. Indus-1 and the beamlines on them are national facilities and scientists from universities, national laboratories, etc. are encouraged to use them.

1. Angal-Kalinin, D. *et al.*, *Curr. Sci.*, 2002, **82** (this issue).
2. Sawhney, K. J. S. and Nandedkar, R. V., *Pramana,* 1994, **42**, 49; *Nucl. Instrum. Methods*, 1995, **A359**, 146.
3. Lodha, G. S., Raghuvanshi, V. K., Modi, M. H., Tripathi, P., Verma, A. and Nandedkar, R. V., *Vacuum* 2001, **60**, 385.
4. Nandedkar, R. V. *et al.*, *Curr. Sci.*, 2002, **82**, (this issue).
5. Chaudhary, S. M. *et al.*, *Curr. Sci.*, 2002, **82** (this issue); Chaudhary, S. M. and Pimple, A. V., *J. Nucl. Instrum. Methods,* 1995, **A359**, 274.
6. Roy, A. P., *Spectroscopy: Prospective and Frontiers* (ed. Roy, A. P.), Narosa Pub. House, New Delhi, 1997, pp. 312–320.

ACKNOWLEDGEMENT. We thank all the members of different beamline teams who have made significant contributions in the design and development of the beamlines.