Aust. J. Phys., 1995, **48**, 321–31

The Pohang Light Source*

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Abstract

A 2 GeV synchrotron light source project is in progress in Pohang, Korea. The light source is designed to provide high brightness radiation with continuous wavelengths down to 1 Å (10^{-8} cm) with its peak at 4·43 Å (i.e. 2·8 keV). The project, consisting of a full energy injector linear accelerator and a 2 GeV storage ring, was launched in 1988 and is scheduled to be completed by the end of 1994. In this article, we introduce the main features and status of the storage ring components and the installation procedure. Radiation characteristics and beamline status are also described.

1. Introduction

Light has been an indispensible tool in the development of science. The advent of laser technology has made it possible to conduct various experiments using intense and coherent light with a particular frequency range. However, many scientific experiments require much wider spectral range including infrared, visible, ultraviolet, and X-ray region. The reason for this is to match the characteristic length of the object under study to the wavelength of the light irradiated. In the 1940s, it was recognised that the radiation emitted from circulating highly relativistic electrons or positrons in a high energy accelerator provides a very intense, directional light with wide spectral range. The name of 'synchrotron radiation' was actually derived from the synchrotron, one such accelerator. It has been realised that, for the study of the structure of matter up to a few Angstroms, synchrotron radiation is almost ideal in both basic and industrial research and development. This includes such areas as condensed matter physics, biology, chemistry, materials science, life sciences, medical science, X-ray lithography, nanomachine fabrication, etc.

Realising this, in 1988 a group at Pohang University of Science and Technology (POSTECH) faculty made an initial investigation of the key areas of light source construction. An energy of 2·0 GeV was chosen because, with this energy the usable photons from bending magnets span wavelengths down to 1 Å, the order

* Refereed paper based on plenary lecture given to the joint Sixth Asia Pacific Physics Conference and Eleventh Australian Institute of Physics Congress held at Griffiths University, Brisbane, July 1994. Work supported by the Pohang Iron and Steel Company and Korean Ministry of Science and Technology.

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0004-9506/95/020321$05.00

of atomic radii. The critical photon energy of the radiation from a bending magnet is defined as

$$E_c(\text{keV}) = 0\cdot 665 \times E^2(\text{GeV}) \times B(\text{T}) , \tag{1}$$

where E is the electron energy and B is the bending magnet field. With a bending magnet field of 1·058 T at an energy of 2 GeV, E_c is 2·8 keV and usable photon energies extend up to about four times E_c. The PLS has been designed to be a third generation machine which is characterised by a low-emittance (typically 4–20 nm rad) electron beam in the storage ring.

The PLS accelerator system consists of a full energy injector linear accelerator and a 2 GeV storage ring (Lee 1993; Namkung *et al.* 1993). The injector linear accelerator is 155 m long and employs eleven klystrons and modulators. The electron gun generates a 2 ns, 2 A electron pulse with a 10 Hz repetition rate. In order to produce a 2 GeV electron beam in such a short length, the maximum klystron power was chosen to be 80 MW and this power was further enhanced through the addition of an energy doubler system. The installation of the linear accelerator was completed in December 1993 and has been under commissioning since then. Recently, it produced a 2 GeV electron beam with reasonable beam quality.

In the following, we describe the characteristics and status of the storage ring and its components. Magnet, vacuum and RF systems will be introduced. The instrument and control system and the scheme for survey and alignment will then be presented. Finally, the radiation characteristics and beamline status will be described.

2. PLS Storage Ring

The storage ring is 280·56 m in circumference and it consists of 12 super-periods with triple bend achromat (TBA) structure. Thus, there is a total of 36 dipole magnets. While a conventional TBA structure employs a dipole magnet with quadrupole focusing to reduce the natural emittance, the PLS storage ring does not utilise such a combined-function dipole. This makes the emittance a little higher, but it has the advantage that the magnet fabrication is much easier, thereby avoiding the difficulty in defining the median plane of the magnet. Each super-period has a mirror symmetric structure. In addition to three dipoles, there is a total of 12 quadrupoles, four sextupoles and six horizontal and vertical combined dipole correctors per super-period. Sextupoles are placed to correct the natural chromaticities in order to cure the head–tail instability. The sextupole, however, is intrinsically a nonlinear device and it therefore limits the maximum stable region of a circulating beam. Fig. 1 illustrates the PLS lattice parameters for one super-period. In the PLS storage ring, the locations and strengths of sextupoles are carefully optimised to minimise nonlinear effects and, as a result, the lattice becomes relatively robust to magnetic multipoles and various magnetic errors.

Fig. 2 shows the dynamic aperture for the PLS storage ring which defines the boundary of the stable region for particle oscillation. Nonlinear effects due to sextupoles manifest themselves by amplitude-dependent tune shifts and nonlinear chromatic effects. The outcome of the amplitude-dependent tune shifts appears

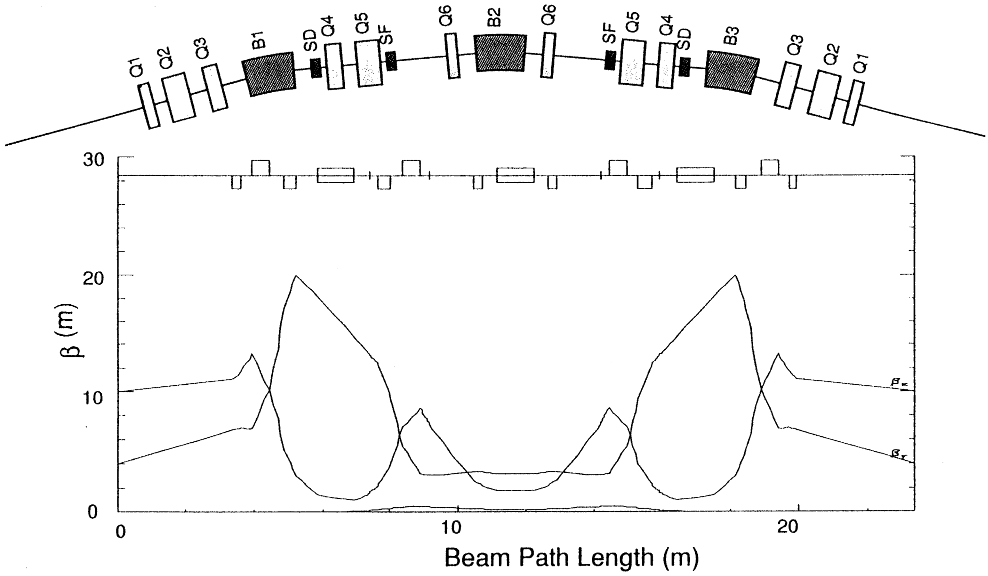

Fig. 1. Lattice parameters of the PLS storage ring.

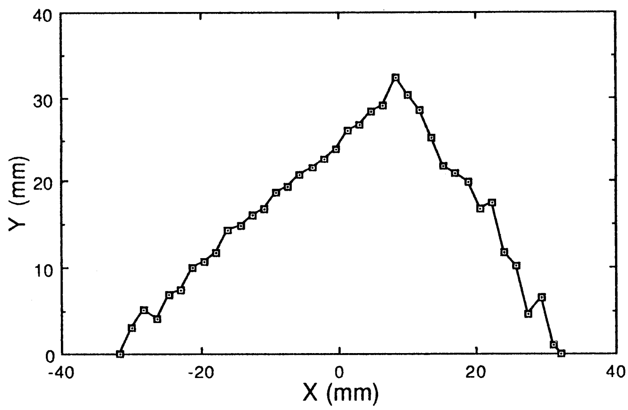

Fig. 2. Dynamic aperture of the PLS storage ring.

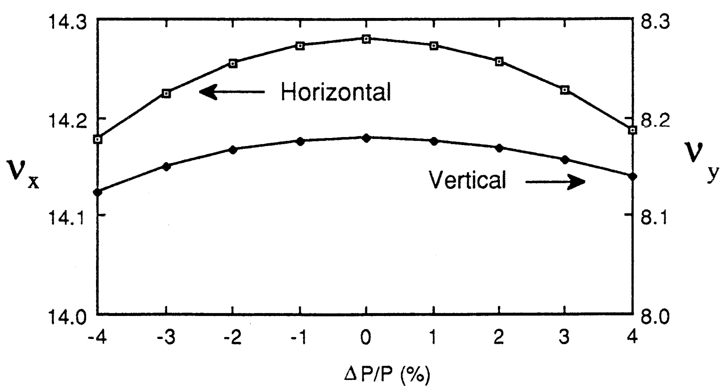

Fig. 3. Horizontal and vertical tune shifts as a function of particle momentum.

antechamber is chosen to minimise RF leakage and possible resonances with the antechamber. Pumping is provided by a number of sputter ion pumps (SIPs) and non-evaporable getter pumps (NEGs). Combination pumps, consisting of lumped NEG and SIP, are provided under each photon stop where unwanted synchrotron radiation strikes and is absorbed. Cooling water is supplied to each photon stop.

In order to minimise impedances, abrupt steps must be avoided inside the vacuum chamber along the beam orbit. In the case where steps are unavoidable such as for bellows, flanges, RF cavities and insertion device vacuum chambers, smooth transitions or RF shieldings are provided. In the PLS, all bellows, flanges and monitors have RF shielding except four beam profile monitors distributed around the ring. However, these profile monitors will be used only during the commissioning period, especially for the first-turn operation, and eventually will be removed after commissioning.

Each super-period has two sector chambers, 7 and 10 m long, and one long straight section where an insertion device is to be placed. Each sector chamber is composed of top and bottom pieces. The two pieces are machined separately by Daewoo Heavy Industry and delivered to the PLS laboratory to be welded together. Aluminum alloy 5083-H321 has been chosen as the chamber material. After chamber closure welding, spool pieces, flanges and pumps are installed and the whole chamber assembly is mounted onto the support girder. This chamber-girder assembly is then ported to the storage ring tunnel. The installation of the chamber-girder assembly began in March 1993 and was completed in January 1994. In-situ bake-out has been carried out for two super-periods out of twelve. Mid 10^{-10} Torr was achieved after bake-out. Bake-out for the remaining ten super-periods is planned for after commissioning.

5. RF System

Energy loss due to synchrotron radiation must be compensated for by a set of RF cavities. The RF cavities are placed in one of the dispersion-free straight sections. Total length available is approximately 4·5 m and eventually there will be five RF cavities. The accelerating frequency is chosen to be 500·082 MHz. The PLS RF cavity is identical to that of the Photon Factory storage ring in Japan and its higher-order mode characteristics are well understood. The RF cavity is the major source of coupled-bunch instabilities. Based on parameters of the Photon Factory RF cavity, which are actually the same as the measured values for the PLS cavity, the coupled-bunch growth rate has been calculated. The result shows that the coherent growth time with SPEAR scaling is about 0·14 ms in the longitudinal direction and 54 ms in the transverse direction respectively. This means that the transverse coupled-bunch instability should not be a problem because the growth time is greater than the damping time which is 16 ms. On the other hand, in the longitudinal direction, the growth time is much less than the longitudinal damping time, which is 8 ms. Therefore, the RF system should include a higher-mode suppressor and proper feedback systems. In the case of the PLS, the higher-order modes are suppressed by the inclusion of tuners as well as blank flanges, while leaving the feedback system as a future option. For each cavity, the shunt impedance is measured to be 8 MΩ.

To provide an overall single-bunch lifetime of more than 3 hours, a voltage of 1·8 MV is required at the energy of 2 GeV with 7 mA beam current. The total

RF power requirement varies from 160 to 344 kW as the stored beam current is increased from 100 to 400 mA. At present, three cavities have been installed and will be used for the commissioning. Even with only three cavities, the injection efficiency should not be significantly affected and Touschek lifetime reduction should not be important during the initial period. After commissioning, one more cavity will be installed and eventually the fifth cavity will be placed when 2·5 GeV operation is required.

The RF building is located in an area of the storage ring tunnel. Three 60 kW CW transmitter stations to feed the three cavities independently were installed together with the necessary high power transmission line components. The in-situ baking and the high power aging of the cavities were carried out in early July 1994 when the low-level RF system was completed.

6. Control System and Instrumentation

The control system is based on a UNIX environment and consists of a host computer, console computers, and VMEbus based data acquisition and control systems (DACS). A hierarchial system architecture was adopted. The DACS consist of subsystem control computers (SCCs), machine interface units (MIUs) and low level communication networks. MIUs are distributed around the ring to reduce the length of the signal cables between MIUs and the machine components as well as to reduce the electromagnetic noise problems on the cables. Each SCC is interconnected to the multiple MIUs through MIL-1553B network. The SCCs are also linked to the high level computers through Ethernet (TCP/IP).

There are a number of beam diagnostic devices distributed around the ring. In the PLS, a total of 108 beam position monitors (BPMs) is installed. Each BPM employs four button-type electrodes and one BPM per each super-period has the capability of measuring turn-by-turn information of a beam which will be helpful during the first turn operation. All BPMs are aligned with respect to the magnetic centre of the adjacent magnet within ± 1 mm in order to ensure linearity. After installation, calibration of all BPMs has been done in the ring and the results together with the alignment data will be included in the database. Other beam diagnostic instruments include a direct current current transformer (DCCT) which gives information on beam lifetime and average current; five beam profile monitors; one beam scraper; a stripline kicker and monitor to measure the tunes, and a photon beam monitor. In addition, there are stripline monitors just before the injection septum magnet that will provide phase space information on the injected beam. Of the five beam profile monitors, four are not impedance-matched, and therefore should be removed when the beam current becomes high. The purpose of these profile monitors is just to diagnose the first turn operation during the commissioning by showing a rough location of the beam loss.

7. Survey and Alignment

Because of having a low emittance and thus high tunes, this third-generation machine is very sensitive to various magnetic errors. The rms positioning tolerances of the PLS storage ring magnets are: 0·5 mm for the dipole magnet, 0·15 mm for the quadrupole magnet, 0·2 mm for the sextupole magnet, and 0·5 mrad for magnet rotation with respect to the longitudinal axis. Among them, the transverse positioning error of the quadrupole magnets yields the largest closed orbit amplification factor and this is the reason why its tolerance is tighter than for the others. In order to meet such a tight alignment requirement, ten geodetic control points are established, six inside the storage ring and linac buildings and four in the hill area outside the buildings. A relative accuracy better than $0 \cdot 5$ mm rms is achieved. In addition to these geodetic points, a number of tunnel control points are installed to establish a tunnel survey network. In order to minimise the centring error, a total of 72 wall brackets are mounted on the inner wall of the storage ring tunnel. In addition, there are 32 wall brackets in the beam transfer line tunnel. All the directions and distances are measured with electronic theodolites and electronic distance meters respectively. A relative accuracy of $0 \cdot 2$ mm rms is achieved.

There are four stages for the alignment of the storage ring components; prealignment, rough setting, fine positioning, and smoothing. The prealignment process involves a vacuum chamber align with respect to the girder coordinate system. For this purpose, a number of fiducial marks are installed on the girder plate. A relative accuracy of $0 \cdot 2$ mm rms is achieved. The prealigned girder assembly is transported into the tunnel and positioned roughly on the floor marks. All magnets are positioned on their struts on the girder. Because of the small gap between magnet and vacuum chamber, an accuracy of ± 1 mm is required for rough setting. The girder and magnets roughly positioned are adjusted to a relative accuracy of $0 \cdot 2$ mm with respect to the control points inside the ring tunnel, using an electronic theodolite. Several iterations of surveying and alignment are carried out at this stage. Smoothing involves a set of successive overlapping measurements of the local curvature using a metrological chain of triangles formed by the storage ring quadrupoles. The control points are no longer referenced at this stage. An accuracy of $0 \cdot 15$ mm rms is required and is expected to be achieved.

Fig. 5 illustrates an inside view of the storage ring tunnel.

8. Radiation Characteristics and Beamlines

As described above, third generation storage rings are characterised by a low-emittance (typically 4–20 nm rad) electron beam which directly translates into high brightness synchrotron radiation. The brightness $\mathcal{B}$ is defined as

$$\mathcal{B} = \frac{\text{number of photons/sec}}{\text{mm}^2\ \text{mrad}^2\ \Delta\lambda/\lambda}\,, \tag{2}$$

where $\Delta\lambda/\lambda$ is a fractional bandwidth usually taken as $\Delta\lambda/\lambda = 0 \cdot 1\%$. The small values in the denominator in (2), i.e. small source area, divergence and fractional bandwidth, are closely related to a high degree of coherence. Therefore, the coherent power is an important feature of the third-generation radiation source and has many areas of application, including X-ray microscopy, diffraction, holography, interferometry, etc.

There are two different types of radiation source in a storage ring, one originating from a bending magnet region and the other from an insertion device which is installed in the long straight section of the ring. The insertion device consists of an array of permanent (or superconducting) magnets which produces an alternating magnetic field perpendicular to the orbital electron motion, and

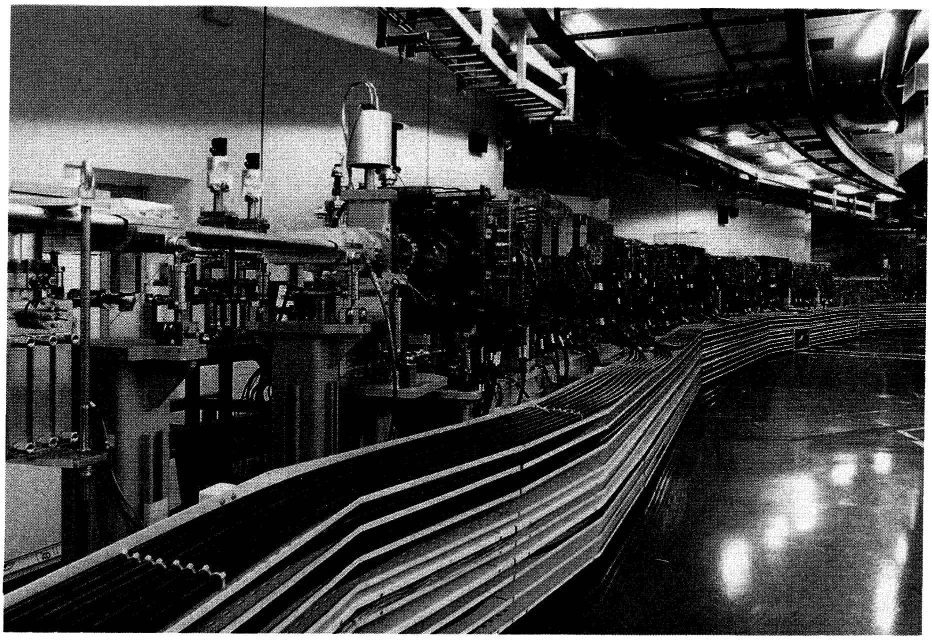

Fig. 5. Inside view of the storage ring tunnel showing a part of the in-stalled storage-ring components.

therefore causes the electrons to go through a periodic wiggling motion. There are two different types of insertion device depending on the deflection parameter $K = 0 \cdot 934 B(\mathrm{T}) \lambda_{\mathrm{u}}(\mathrm{cm})$, where λ_{u} is the length of one magnet period. When $K \leq 1$, the device is called an undulator, but wiggler when $K \gg 1$.

Since the electrons in the undulator make a very gentle wiggling motion, the maximum angular deviation of the electron trajectory is mostly within the natural opening angle of the synchrotron radiation cone. This makes the radiation emitted from successive undulator periods add coherently. The interference effect due to the coherence produces a sharply peaked fundamental and several harmonics. The vertical and horizontal divergence of the undulator radiation is also considerably reduced, depending on the number of magnet periods. Although the radiation energy contained in the narrow bandwidth is much smaller than the total energy of the bending magnet radiation, the undulator radiation gives rise to much higher spectral brightness.

The PLS storage ring will provide a total of 32 beamports, 22 from bending magnets and 10 from insertion devices. However, each beamline can be split into two or three as the need arises.

As mentioned in Section 1, the PLS bending magnet has a field strength of 1·058 T, which produces a broad spectral profile with a critical photon energy of 2·8 keV at 2 GeV electron energy, as shown in Fig. 6. This figure shows the spectral brightness of photons from a bending magnet and from various insertion devices, assuming 100 mA electron beam current. The length of straight section is 6·8 m but the available length for an insertion device is about 4·3 m. A three pole superconducting wiggler with a maximum field of 7·5 T is under construction in collaboration with the Budker Institute of Nuclear Physics, Russia. This

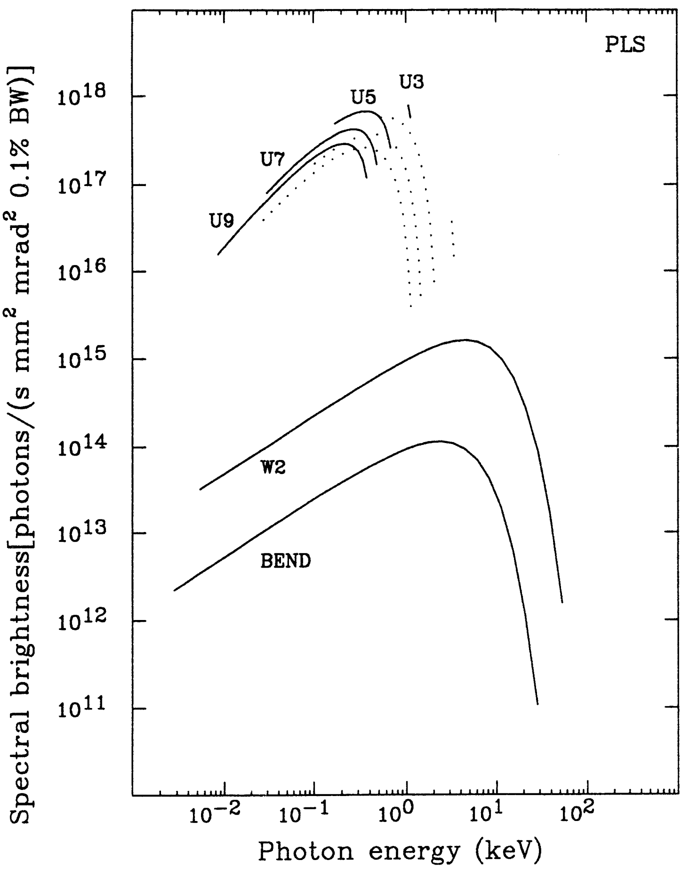

Fig. 6. Spectral brightness as a function of photon energy. Here the electron energy and the beam current are assumed to be 2 GeV and 100 mA.

Table 2. PLS insertion device (ID) parameters

ID*	Period (cm)	No. of periods	Peak field (T)
U3	3·0	140	0·22
U5	5·0	80	0·56
U7	7·0	60	0·90
U9	9·0	48	1·18
W2	15	20	2·0
W7	90	1	7·5

* U is for undulator and W for wiggler.

wiggler will provide broad band, hard X-radiation up to 30 keV photon energy. Also, the design work for an undulator U9 as a soft X-ray source is in progress. Table 2 summarises some parameters for possible PLS insertion devices.

Every beamline is connected to the sector chamber through a front-end, composed of a photon mask, a photon shutter, a fast closing valve, and a pneumatic gate valve.

In the initial phase, there will be two experimental beamlines from a bending magnet, for VUV and X-ray use respectively. The VUV beamline under construction is a Dragon type (Chen 1987) spherical grating monochromator (SGM) system, which consists of a Kirkpatrick–Baez type condensing system, fixed entrance slit, spherical gratings, a movable exit slit and a refocusing mirror. The condensing system accepts 10 mrad of synchrotron radiation horizontally and 2 mrad vertically. The grating chamber of the SGM houses five exchangeable laminar gratings to deliver photon energies from 12 to 1230 eV mainly for photoemission studies. The photon path from the gratings to the movable exit slit is divided into two to accommodate the wide spectral energy range, and joined just before the exit slit by two plane folding mirrors. For spin polarised photoemission studies, a chopper system will be used. This can deliver either left or right circularly polarised light. The beamline will also accommodate a normal incidence monochromator (NIM) system for low photon energies (2–30 eV). For the initial stage of operation, only the one VUV beamline will serve the VUV beamline users and, to serve as many users as possible, the beamline has been designed to provide wide spectral energy range and high energy-resolution.

For X-ray beamlines, one EXAFS and one diffraction beamline are currently planned. The EXAFS beamline is composed of a two-channel-cut Si crystal monochromator followed by a post-focusing mirror and will accept 3 mrad of synchrotron radiation horizontally from the bending magnet. The monochromator provides a fixed-exit beam. The mirror will have the shape of a bent cylinder and will be made of Pt plated Zerodur. The operating range of the beamline is between 4 to 12 keV. The X-ray diffraction beamline has a similar configuration to the EXAFS beamline except for the existence of a pre-focusing bent cylindrical mirror instead of a post focusing one.

In normal operation mode, the time structure of the PLS radiation will consist of 20–50 ps (FWHM) pulses with a minimum separation of 2 ns between pulses.

9. Conclusion

Synchrotron radiation is a powerful research tool in diverse fields of science and technology. Particularly with the advent of third-generation machines, a new horizon of exciting research is now opened. The usefulness of the radiation stems from the fact that the source provides high brightness, tunable (over a wide spectral range), partially coherent, and polarised (linearly or circularly) light.

The PLS project which was started in April 1988 will be completed by the end of 1994. The 2 GeV injector linear accelerator has already been completed and the machine integration of the storage ring is now at its final stage. The commissioning of the PLS is scheduled in September 1994. Starting from mid-1995 the facility will be opened to national as well as international users.

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Manuscript received 6 July, accepted 20 September 1994