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# PROPOSALS FOR SYNCHROTRON LIGHT SOURCES

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## Introduction

Ever since it was first applied in the 1960's synchrotron radiation from an accelerating electron beam has been gaining popularity as a powerful tool for research and development in a wide variety of fields of science and technology. By now there are some 20 facilities operating either parasitically or dedicatedly for synchrotron radiation research in different parts of the world. In addition there are another 20 facilities either in construction or in various stages of proposal and design. These are listed in Table 1.

Table 1 Future Synchrotron Radiation Facilities

| Location | Name | Energy (GeV) | Status |
|---|---|---|---|
| Brazil | - | 2-3 | planning |
| China | | | |
| Beijing | BEPC | 2.8 | construction† |
| Hefei | HESYRL | 0.8 | construction |
| Europe | | | |
| Grenoble | ESRF | 5 | planning |
| France | | | |
| Orsay | SuperACO | 0.8 | construction |
| Germany | | | |
| West Berlin | COSY | 0.56 | construction |
| India | | | |
| Poona | | 1.5 | planning |
| Japan | | | |
| Tokyo | SuperSOR | 1.0 | planning |
| Tsukuba (KEK) | Accumulator | 6-8 | construction† |
| Tsukuba (KEK) | Tristan | 30 | construction† |
| Sweden | | | |
| Lund | MAX | 0.55 | construction |
| Taiwan | | | |
| Hsin Chu | TLS | 1.0 | planning |
| U.S.A. | | | |
| Berkeley | ALS | 1.3 | planning |
| Ithaca | New Ring | 5-6 | planning |
| Stanford | PEP | 15 | construction† |
| | SXRL | 1.0 | construction† |
| To be determined | - | 6 | planning |
| U.S.S.R. | | | |
| Moscow | Kurchatov-I | 0.45 | construction |
| | Kurchatov-II | 2.5 | planning |

†These are $e^{\pm}$ colliding beam machines sharing operation as synchrotron radiation sources.

It is interesting to note from the table that all of the new machines are proposed as dedicated synchrotron radiation facilities. Also remarkable is that the energies of the proposed dedicated machines span over a wide range from 0.45 GeV of Kurchatov-I to 6 GeV of the U.S. national machine. This is an indication of the continued vitality of the research and development activities utilizing synchrotron radiation over the full range of energy.

The experiences gained from the operating facilities and the recent development of insertion devices such as wigglers and undulators as radiation sources led to a new set of requirements on the design of synchrotron radiation storage rings for optimum utility. The surprisingly uniform applicability and unanimous acceptance of these criteria give assurance that they are indeed valid criteria derived from mature considerations and experiences. Instead of describing the design of each of these new facilities it is, thus, more effective to discuss these desirable design features and indicate how they are incorporated in the design using machines listed in Table 1 as examples.

The choice of energy of the storage ring is often given by the energy of the photons that can be produced in an undulator. For example, the 5 GeV of ESRF and the 6 GeV of the U.S. national machine are such that photons of energies 14 keV and 20 keV can be produced in the fundamental mode of an undulator. These photon energies are prescribed, in turn, by specific experimental needs.

## General Requirements

A. Insertion devices as primary radiation sources- Both the brilliance (photons per unit source area per unit solid angle, per unit relative bandwidth and per unit time) and the critical energy (or frequency) of the radiations from insertion devices (ID's) could be much higher than those from the bending magnets. Therefore, the storage ring should be designed to accommodate a large number of ID's.

B. High beam current and low emittance - The brilliance of the radiation is proportional directly to the beam current and inversely to the square of the emittance. Low emittance is, thus, even more beneficial than high current.

C. Flexibility - The storage ring should be capable of accepting an arbitrary mix of ID's and the beam characteristics in the ID's should be individually adjustable to optimize the performance. A well designed control system is essential.

D. Stability - The beam should be stable both electrically and mechanically, and have a long storage lifetime.

E. Simple and reliable operation - This requires reliable hardware, good vacuum, precision regulated power supplies, good controls, noise-free foundation and environment, adequate and efficient experimental floor space, fast refilling with minimum disturbance on experiments, etc.

## Storage Ring Magnet Lattice

Since circumference is an asset for a synchrotron radiation storage ring the bending magnetic field intensity chosen tends to be rather low, generally in the neighborhood of 1 tesla. Although not a principal consideration the low field also reduces the power consumption. The lattice will contain a large number of long straight sections to accommodate insertion devices. The energy dispersion in these straight sections should be zero. A free length of 6 m is generally considered adequate. Special applications for free-electron-lasers have been suggested which may require lengths up to 20 m. If firmly

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established in the future, these needs will certainly also be incorporated in the design.

With any magnet lattice the equilibrium beam emittance $\varepsilon$ is given by $\varepsilon \cong \kappa\gamma^2\theta^3$ where $\gamma$ = beam energy in $mc^2$ units, and $\theta$ is the average bending angle of the bending magnets. The proportionality constant $\kappa$ depends sensitively on the lattice type and can range over two orders of magnitude. The smallest $\kappa$ is obtained for the Chasman/Green lattice*,[1]. However, because of the rather violent focusing required for the Chasman/Green lattice the chromaticity sextupoles required tend to be rather strong, the stable dynamic apertures tend to be rather small and the lattice tends to be rather sensitive to imperfections in construction. Nevertheless, for a properly designed Chasman/Green lattice the available dynamic aperture is adequate and the sensitivity to imperfections is tolerable. Although variations have been suggested[2,3] most of the new proposals[4,5,7] adopt some type of Chasman/Green lattice and obtain emittances in the range of $10^{-8} - 10^{-9}$ $\pi$m-rad.

Each straight section should have a central drift space of about 6 m and a number of quadrupoles located at each end for betatron matching. Two quadrupoles at each end is the minimum, three quadrupoles will provide the flexibility of adjusting for different $\beta$-values in the insertion device located in the central drift space.

At least two sets of sextupoles are needed, one each at high horizontal and high vertical-$\beta$ locations where dispersion is large. More sets may be required, some located possibly in zero-dispersion sites, to kill harmful harmonics to enlarge the dynamic apertures to acceptable values. Typically the dynamic aperture should be more than ~50 times the rms beam size. The dynamic aperture is computed now exclusively by orbit tracking computer programs. Efforts are being spent on verifying or confirming the tracking results by either analytical calculation or experimental measurement. The design beam lifetime which is determined by the quantum fluctuation, the multiple Coulomb scattering, the Touschek effect, and the intra-beam scattering should not be less than 5-10 hours. The beam should also be free from all coherent instabilities.

General parameters for ALS[4] and ESRF[5] are given in Tables 2 and 3. Their lattices and orbit functions are shown in Figures 1 and 2.

Table 2 General Parameters of ALS

| | |
|---|---|
| Electron energy (GeV) | 1.3 |
| Electron current (mA) | 400 |
| Circumference (m) | 182.4 |
| Number of superperiods | 12 |
| Number of long straight sections | 12 |
| Length of long straight sections (m) | 6 |
| Dipole field (T) | 1.09 |
| Maximum quadrupole gradient (T/m) | 15.7 |
| Maximum sextupole gradient (T/m$^2$) | 570 |
| Horizontal emittance ($\pi$m-rad) | $6.8\times10^{-9}$ |
| Horizontal tune | 13.8 |
| Vertical tune | 7.8 |
| Radiofrequency (MHz) | 499.65 |
| Harmonic number | 304 |

*The generalized Chasman/Green lattice is here defined as one in which the neighboring zero-dispersion straight sections are joined by an achromatic bend composed of only two bending magnets and any number of quadrupoles.

Table 3 General Parameters of ESRF

| | |
|---|---|
| Electron energy (GeV) | 5 |
| Electron current (mA) | 100 - 200 |
| Circumference (m) | 776.3 |
| Number of superperiods | 16 |
| Number of straight sections | 32 |
| Length of straight sections (m) | 5.3 and 3.0 |
| Dipole field (T) | 0.833 |
| Maximum quadrupole gradient (T/m) | 16.0 |
| Maximum sextupole gradient (T/m$^2$) | 264.6 |
| Horizontal emittance ($\pi$m-rad) | $7.2\times10^{-9}$ |
| Horizontal tune | 34.23 |
| Vertical tune | 22.19 |
| Radiofrequency (MHz) | 352.2 |
| Harmonic number | 912 |

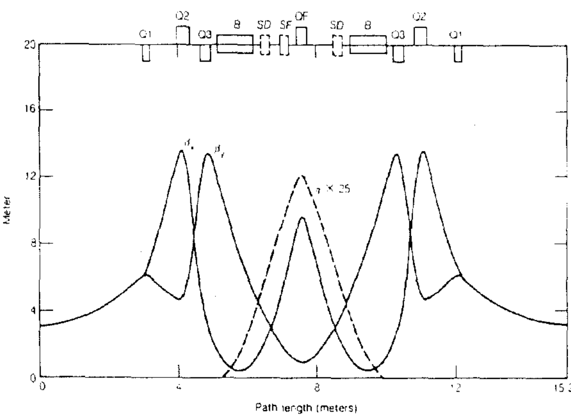


Figure 1 ALS magnet lattice and orbit functions

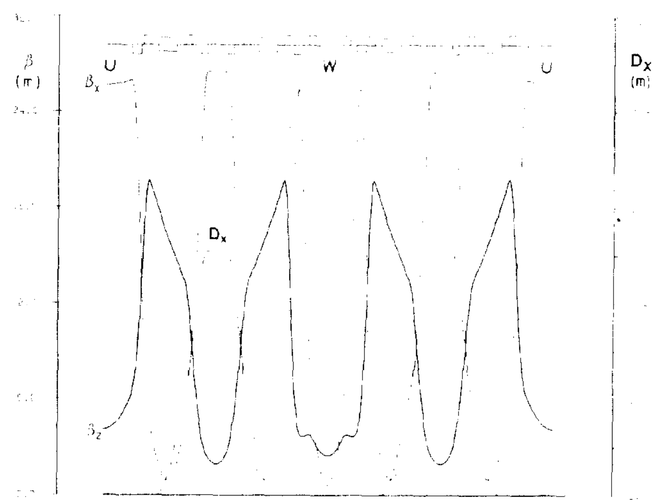


Figure 2 ESRF magnet lattice and orbit functions

## Injector

Full energy injection is almost universally adopted. Although this implies a higher injector cost it is generally believed that the advantages derived are well worth the cost. The advantages are:

A. The maximum beam current obtainable is limited by the beam lifetime which is shortest at the low injection energy. All storage rings with full energy injection have operated at higher beam currents.

B. To re-fill the ring at full energy all one has to do is to "top-up" the current. This is a much simpler operation than to re-inject and re-accelerate a new beam, and imposes much less disturbance on the experiments.

C. Perhaps the most important advantage is the total d.c. operation of the storage ring. Without ramping, once the beam lines, the photon lines and the experimental equipment are tuned up, data can be taken under exactly invariant conditions even though the beam has to be topped up from time to time. Furthermore, much higher accuracy and stability can be obtained with d.c. power supplies and other d.c. equipment.

The beam particles can be either electrons or positrons. Being positively charged a positron beam does not trap positively charged ions and are, thus, free of all ion induced instabilities. Clearing electrodes which suck positive ions out of a negative electron beam have been applied and found to be effective. But the general belief is mounting that a beam which is naturally more stable is perhaps worth the more costly positron generator and damper.

A standard positron pre-injector consists of a high current electron linac (~5 A and ~200 MeV), a converter target, followed by a low current positron linac. If only electron injection is needed the electron beam can be supplied either by a low current linac or by an inexpensive microtron. The ESRF and the ALS choose electron beams with positron options whereas the 6-GeV U.S. national machine[6] opts for a positron beam ab initio. The full energy injector is usually a moderately fast cycling (1-10 Hz) synchrotron. Without the need for long straight sections and with the use of higher field intensity the booster synchrotron can have a circumference less than half that of the storage ring. In the Argonne 6-GeV design[7] the circumference ratio is exactly one half. For the ESRF the circumference ratio is chosen to be 7/19. This allows selective filling of specific rf buckets in the storage ring by cogging.

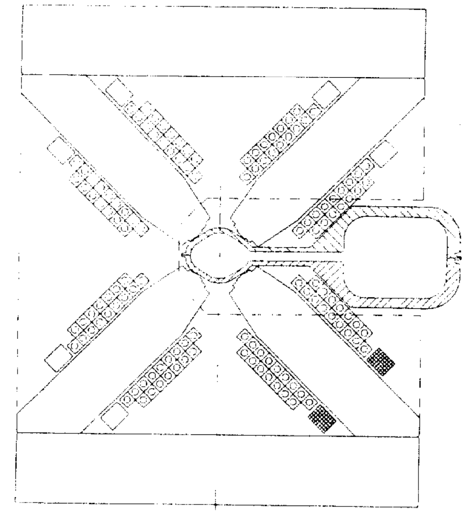

Figure 3 ALS C-quadrupole. The quadrupole body is composed of separate top and bottom pieces held together by strong C-shaped end plates shown in dotted lines.

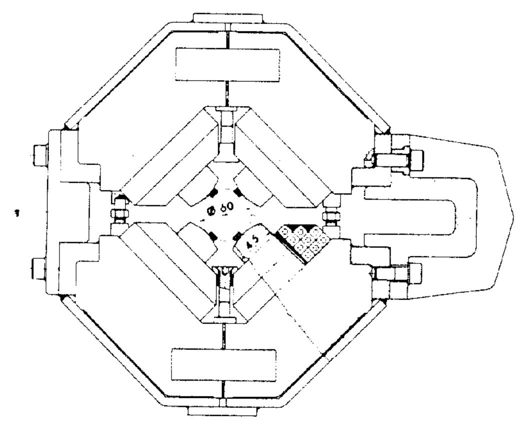

Figure 4 Cross-section of the ESRF "split" quadrupole

## Ring Magnets

At the low field adopted for the storage ring the field design of the ring magnets presents no difficulty. To let through the synchrotron radiation the C-design is generally used for the dipole and, in some cases, also the quadrupole. The cross-section of the ALS C-quadrupole and that of the ESRF "split"-quadrupole are shown in Figures 3 and 4. In some designs it is even necessary to have C-sextupoles. Current regulations and ripples must be better than $10^{-4}$. This is not difficult to attain for d.c. power supplies. The usual complement of trim multipoles up to sextupoles or octupoles is used to adjust for optimal operation.

## Vacuum System

The vacuum system is perhaps the single most important component for obtaining optimal performance. The no-beam vacuum of $<10^{-10}$ Torr is not difficult to achieve. The difficulty is in maintaining a dynamic vacuum of $<10^{-9}$ Torr when the vacuum chamber wall is flooded with intense synchrotron radiation from the high current beam and turns into a powerful source of copious photodesorbed gas molecules. The design efforts have concentrated in four areas.

A. Chamber material - Favorite ones are aluminum and stainless steel. Aluminum vacuum chamber is easier to fabricate by extrusion, is simpler to clean, bakes out at lower temperature, and has a lower desorption rate. The only drawback is that aluminum/stainless steel transitions are complicated and costly if stainless steel vacuum components are also used. All aluminum systems have been developed[8], but some aluminum components are expensive to fabricate and difficult to handle. The ESRF elected to use an all stainless steel system. In most other designs aluminum chambers are chosen.

B. Chamber geometry - It is advantageous to divide the vacuum chamber into two parts: the electron beam chamber on the inner radius side and the radiation absorber chamber on the outside, and isolate the two parts by baffles so that the outgassing in the absorber chamber is pumped out immediately and does not back-stream into the beam chamber. However, the rf characteristics and the "impedance" of the baffle as viewed by the beam must be studied and measured to ensure that it does not cause instabilities in the beam.

C. Absorber/pump geometry - Two distinct styles are possible in the absorber design: localized or distributed. If the absorber chamber is sufficiently wide the radiation will strike only the absorber mounted in the middle of the chamber at the downstream end (identified as "crotch" in Figure 5). The localized

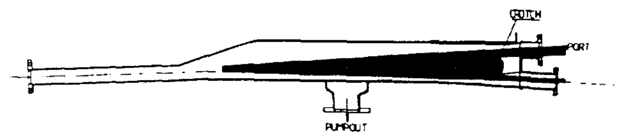

Figure 5 Plan view of vacuum chamber with localized absorber - indicated as "crotch". The shaded area is filled with synchrotron radiation.

outgassing from the absorber is pumped by high speed pumps located right next to the absorber. On the other hand, if the absorber is a long strip mounted on the outer wall of the chamber the outgassing will be distributed and must be pumped by distributed pumps. The cross-section of the vacuum chamber will then look like that shown in Figure 6. Further studies are needed to determine which style is more effective. The ESRF adopts localized outgassing/pumping and both the ALS and the Argonne 6-GeV design use aluminum chambers with mostly distributed absorber and pumping.

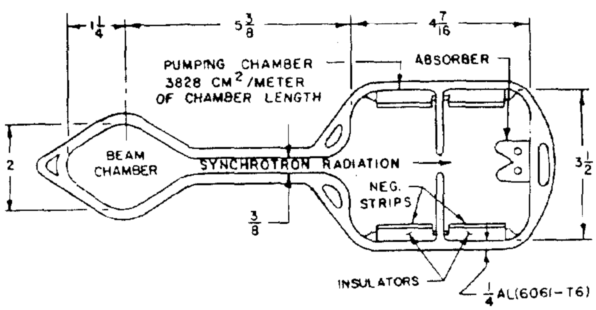


Figure 6 Cross-section of vacuum chamber with distributed absorber and pumping.

D. Pumps - Lumped and distributed ion pumps have been the work horse. Recently sublimation and non-evaporative getter pumps are coming into use. Perhaps someday cryo-pumps will find application. Research and development efforts on new simple, reliable, high speed, lumped and distributed pumps will have major payoffs.

Radiofrequency System

For a certain class of experiments of the time-of-flight type short beam bunches and long intervals between bunches are desired. Therefore the new generation of proposed machines have all gone to much higher frequency rf systems. The detailed choice is based on the availability of klystrons as power sources. The ESRF chose to use the 350-MHz 1-MW klystron developed by CERN for LEP. The ALS uses the 500-MHz 300-kW VKP-8259 klystron. The base rf voltage and power requirements are given by the radiation from the ring dipoles and from projected mixes of insertion devices, and by the cavity loss. The over-voltage is determined by the need for adequate quantum and Touschek lifetimes. The cavity can be either single or multiple cells. Single cells contain fewer high order modes, but multi-cell cavities have higher shunt impedances. The rf power is transmitted to the storage ring by wave guides and coupled to the cavities through vacuum windows.

Insertion Devices

The wiggler, sometimes referred to as the wavelength shifter, uses high field such as the 5 tesla produced by superconducting dipoles to reach high photon energy. A minimum of 3 bends are necessary to restore the beam orbit. More wiggles can be added to increase the photon flux. Wigglers produce a great deal of total radiation power, generally tens of kilowatts.

The undulator gets high brilliance by coherently superposing the radiation from a large number of wiggles or periods. Permanent magnets made of high field material such as Sm-Co or Nd-Fe are used to form structures with periodic lengths of several centimeters. The radiation emitted is concentrated in narrow frequency bands at the harmonic frequencies corresponding to the wiggling period. Although the brilliance is high the total power radiated is low, frequently less than 1 kW. The transverse beam size or the $\beta$-function in the insertion device is adjusted to optimize its performance. For intense wiggler radiation one wants small $\beta$ values and for maximum brilliance from an undulator the optimal $\beta$ is roughly equal to the total length of the undulator which may be as much as 5 meters. The detailed optimization involves the $\beta$-values in both transverse planes.[9]

Beam Tuning and Control Systems

Although some unusual demands are made on these systems no new philosophy had to be developed to cope with these demands. For instance, the condition for stability of the beam in the ID is quite stringent. The photon beam produced from an undulator must not jitter more than its divergence angle of $(\gamma\sqrt{N})^{-1}$ (N = total number of periods) which can be $\lesssim 10\ \mu$rad at high energies. There are, of course, steering dipoles at either end of the straight section to fine trim the aiming of the light beam and to which a feedback steering system can be applied. But the foundation of the storage ring, the photon beam line, and the experimental apparatus must be very stable and so designed as to absorb as much as possible all "noises", and all ancillary machineries which may cause ground vibration must be removed to sites far away from the storage ring.

One slightly novel feature of the operation of the storage ring is that the beam properties in each straight section should be tuned to optimize the performance of the specific ID in that straight section. It is, therefore, likely that the tuning of all straight sections is different and needs to be changed for some ID's in the middle of a run. For such a mode of operation on-line and real-time operations simulation capability is clearly required of the control system.

Future Outlook

It is clear from the above discussion that synchrotron radiation facilities of all energies will continue to be in demand for both scientific and industrial research and development. Many more such machines can be expected to be built in the coming years. But it is also evident that the requirements hence the desired design features of these facilities are, by now, pretty well understood. The design of this new generation of machines is fairly well optimized and will unlikely undergo major changes in the future.

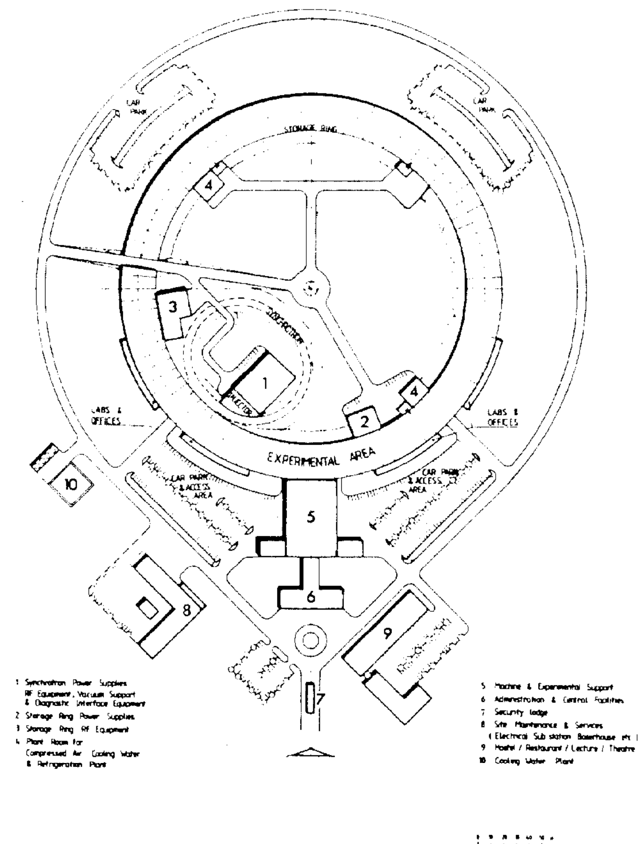


Figure 7 Site layout of ESRF

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