A Review of Proposed New European Synchrotron Light Sources

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Abstract

There are a number of new proposals for European synchrotron light sources that are designed to meet national needs for access to high brilliance and high flux beams of radiation. A review is made of these proposals, emphasising the contrasting accelerator solutions and in particular how these differ from existing projects.

1. WHY MORE SOURCES ?

At the time of the last EPAC Conference a comprehensive review [1] suggested a world total of 54 storage rings for synchrotron radiation either operational or under construction. In the two years since then there have been 5 new sources commissioned : CAMD and ALS in the USA; SRRC in Taiwan; and in Europe ELETTRA and the ESRF. Of these only CAMD is not a 3rd generation light source and the others have greatly increased the availability of high quality synchrotron radiation beams to the user community. What is the nature of this user demand that has led to yet more proposals even in Europe ?

Synchrotron radiation has become a prime tool for research in a range of disciplines that includes biology and biotechnology, materials science, physics and chemistry. In addition to the academic research base it has attracted industrial users such as drug companies, semiconductor device manufacturers and many others. At the lowest photon energies infra-red beam lines have been provided but the main interest commences at about 5 eV, extends through the VUV into the increasingly important soft x-ray region above 100 eV, and attracts an enormous user population between 1 keV and 30-50 keV with a very small group at even higher energy. In Europe alone it is estimated that the user community will soon exceed 10,000 active scientists and it is against this background that further project proposals must be seen.

In this review it is not appropriate to consider the merits of the scientific cases that have been generated but they are clearly very strong. Of more interest here is to assess the source characteristics that are being requested and how these have influenced the design solutions. Only European facilities and requirements will be discussed.

2. USER NEEDS AND MAJOR SOURCE CHARACTERISTICS

There is now a well-established, mature user community that has considerable experience in exploiting European synchrotron radiation facilities and this has been an important element in setting the specifications for the new proposals. Each country has traditional strengths that are reflected in their own choice of specification priorities. Another important factor is the present availability of a light source, noting that despite some tendency to internationalisation many users only require a few days access to the source and therefore are reluctant to travel far. As will be seen, even where a national source is already available it is necessary to consider alternatives for some users, perhaps so that a highly optimised output can be obtained. One example of this is the ESRF [2] that provides extremely brilliant beams above 1 keV from its 6 GeV electrons. For those countries that are members of this project it is impossible to ignore its high quality source characteristics and any national solution will have to be a complementary facility.

There are already many funded light sources projects in Europe of which 9 storage rings are now operational and fully dedicated : 3 in France, 2 in Germany and single facilities in Sweden, Italy, Russia and the UK. A further 4 will be commissioned in the future (MAX-2, BESSY-2, TNK and SIBERIA-2) but this only consolidates the position of these six countries. Of the new proposals 3 involve additional nations: Switzerland (SLS), Spain (CLS) and the Ukraine (PSR and ISI). The remainder are in the UK (SINBAD and DIAMOND), France (SOLEIL) and Germany (ROSY). Although other facility proposals have been made, especially in Germany, these will not be discussed here as they are believed not to be likely to be funded. There is little recent information on the status of the earlier 2 GeV PSR project [3] in Kharkov and it was not a dedicated source, so it will not be discussed further. It must also be borne in mind that by their nature project proposals evolve and some of the information presented here may already be out of date.

Since the first generation of (parasitic) sources the history of their development has been the desire to match their performance to the changing needs of user communities that have emerged. In some countries a single dedicated source has had to cover a wide spectrum of photon energies (eg the SRS at Daresbury and the Photon Factory in Japan) but in other cases even second generation rings became more specialised, such as the two NSLS rings at Brookhaven and the use of ACO and DCI at Orsay. With the recent appearance of the third generation sources this process has been consolidated by the fact that they rely so heavily on the use of undulators to produce high brilliance radiation. These undulators can only deliver optimised performance over a limited photon energy range so that the previous advantage of broad band output from storage ring bending magnets has been lost. Depending on the number of undulator harmonics that can be exploited the useful range is usually considered to be a ratio of about 20-40. It is clear that the energy of the storage ring has therefore become a critical choice and the new proposals all reflect this. In practice a decision must be made whether to optimise for VUV, soft x-ray or hard x-ray communities, although of course lower quality radiation is still available from the bending magnets.

The latest group of third generation European sources have made radiation brilliance their highest priority with the rings SuperACO, ESRF, ELETTRA, MAX-2 and BESSY-2 all having extremely small electron beam emittances, generally less than 10 nm-rad. The operating members of this group have confirmed that the basic design principles for such rings are now well understood and their performance can be confidently predicted [4]. However brilliance is not the only parameter of high importance to users and a number of the new proposals have not joined the quest for ultra-low emittance. It is clear that for many experiments the photon flux delivered to the sample is not increased by reducing the electron source dimensions beyond a certain limit, although of course there will always be other applications (eg very small samples, imaging, coherence) where brilliance is vital.

In setting the specifications of these new proposals it will be seen that their designers have also given attention to flux, beam lifetime and the bunch structure needed for time resolved work. Even for energies in the 2-3 GeV region the lifetime can be significantly reduced if the rings are operated in their minimum emittance configuration and the highest performance rings in this respect are also most sensitive to errors. The greatest fluxes in a modern light source are generated by multipole wigglers but these also exert a pôtentially damaging influence on the stored beam. It is also noteworthy that third generation sources rarely achieve the stored beam currents of 500 mA or more that were aimed at by their predecessors.

As a final comment at this stage it is of interest to query whether any new proposal can be considered to have novel features meeting the criteria for a fourth generation source. Examples of such criteria include ultra-low emittance (say, less than 1 nm-rad), extremely short bunches (~1 mm) or high coherent power from a free electron laser (FEL). Perhaps only the latter represents a truly generational change but for a high energy FEL it seems essential to provide exceptionally long straights of 10-20 m or more and probably also a bypass capability.

3. SOLEIL : A REPLACEMENT FRENCH SOURCE

French synchrotron radiation users employ the comprehensive facilities of the LURE complex : high energies up to 30 keV from DCI, an old HEP ring now dedicated as a light source, and VUV plus soft x-rays from a modern third generation source SuperACO. This is a mature community of almost 2000 users which is still growing, with a strong emphasis on time resolved experiments that require a source with a small number of intense circulating bunches. The CLIO FEL provides infrared output that can also be synchronised for pump-probe experiments on SuperACO.

In a review of facilities in 1991 it became clear that the LURE installations would become obsolete by the end of the decade and would need to be replaced. The case for a national laboratory was widely accepted and was complementary to the ESRF which provides higher energy output of a more specialised nature. It was also recognised that the volume of French demand could not be met by ESRF or other shared facilities.

The specification was set after wide user consultation and demanded at least 12 insertion devices. High brilliance undulator output from 10 eV to 2 keV is to be complemented by multipole wigglers for high flux. The bending magnets must provide good output to 30 keV and this implies an energy of 2.15 GeV for an assumed 1.6 T field strength. The range might be extended by a possible 4 T superconducting wiggler magnet. At this stage in the design evolution a target circumference of about 200 m was adopted for cost reasons. However other aspects of the specification were equally important and these included high current of 300 mA with good lifetime in excess of 15 hours. A temporal mode with 60 mA in 6 bunches was requested with a 10 hour lifetime.

A design meeting these requirements has been published [5], based on a conventional DBA lattice with 8 cells as shown in figure 1. A relaxed emittance of 35 nm-rad allows high bunch currents (10 mA) with good lifetime. A higher brilliance mode is also possible for multibunch running since it is proposed to operate the ring without the exact achromatic condition. This setting of finite dispersion in the insertion straights gives a factor 2 emittance reduction (such a solution was first proposed at MAX Lab and is now seriously considered at ESRF). The ring has quite long (6 m) straights so a wide variety of advanced insertions is possible and there is also every intention of using the space in the centre of each achromat for undulators too, giving a total of 13 beamlines from straights.

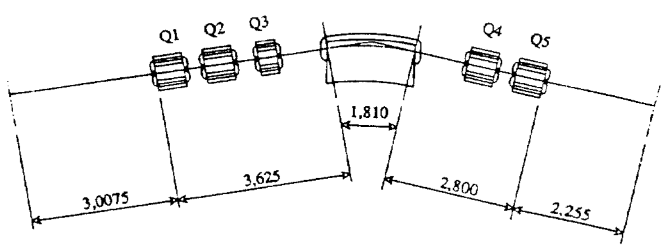

Figure 1. DBA Half Cell for SOLEIL

To obtain good lifetime requires a peak RF voltage of 3 MV and it is proposed to provide this from two superconducting, single cell cavities designed by Cornell for use in a B-factory. The elliptical geometry and large end tubes result in very small higher order mode (hom) content that reduces multibunch instability dangers [6]: the design team rejected a LEP-type cavity for this reason. This would be the first light source with superconducting rf technology.

Based on extensive experience at LURE it is intended to use positrons to remove uncertainties over trapped ions or microparticles. This is the only new proposal to adopt such a solution and would also become unique in Europe. Positrons are produced from 200 MeV electrons in a target, accelerated to 400 MeV and transferred to a full energy booster synchrotron injector. The chosen layout has this injector system located outside the storage ring.

LURE has a tradition of FEL developments and a bypass has been included in the design to allow this to continue. The ring would be reduced to 1.5 GeV for this work and a 12 m straight would be available.

Recently this design has been reassessed and an alternative but much larger ring of about 320 m circumference is now under consideration [7], having at least 12 cells and a correspondingly increased number of insertion devices. This revised lattice could achieve 4 nm-rad emittance for a high brilliance mode if desired but normal operation would still be at 10-30 nm-rad, especially for the few bunch case. Another major change is the addition of two superstraights of 10 m for FEL operation or other exotic insertions.

4. SINBAD AND DIAMOND : THE UK SOLUTION

The scientific case for new UK facilities is based on the necessity to replace the SRS at Daresbury, Europe's leading 2nd generation source. A comprehensive survey of the needs of a community of some 2000 users has led to proposals for both a 700 MeV VUV ring of high brilliance and a high flux, medium brilliance x-ray source of much higher energy [8]. The low energy SINBAD ring meets the user needs for high quality radiation of 5-200 eV from undulators whereas DIAMOND at 3 GeV has high brilliance undulators operating from about 150 eV to a few keV together with very high fluxes at 5-30 keV from multipole wigglers. The survey suggests that some 20 % of all potential users require radiation below 100 eV and the VUV ring is designed to meet this level of demand. In contrast about 60 % of the UK user base require a source for materials science or structural biology and the DIAMOND specification is designed to satisfy this. The largest user group want output in the range 4-30 keV but a significant soft x-ray community must also be included on the high energy ring. Only a minority of users of hard x-rays need the most extreme brilliances and this has strongly influenced the DIAMOND specification. ESRF availability is also important but only for about 10 % of all UK users for whom the combination of high energy and brilliance is essential.

SINBAD has an 8-cell racetrack DBA lattice with 6 normal 3 m straights but also 2 superstraights of 15 m completing the 116 m circumference. The full layout in figure 2 includes the extra matching quadrupoles of the superstraights.

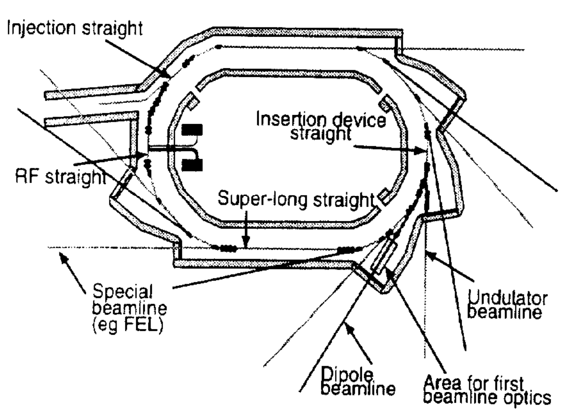

Figure 2. The SINBAD VUV Ring

Emittances of 10 nm-rad or better will be possible and 300 mA beam current has been specified. It is also intended to provide up to 50 mA in a single bunch for the important time resolved user studies. The high peak currents will permit FEL experiments, perhaps making use of a bypass for very small magnet gaps or high gain regime studies able to generate intense coherent XUV output up 10-20 eV. Minimum gaps of about 10 mm in the main ring lattice are dictated by the desire for an adequate gas scattering beam lifetime of at least 5 hours. A single cell 500 MHz cavity provides sufficient momentum acceptance and power replacement. If the ring were to be built at Daresbury then it could make use of the present SRS booster synchrotron, slightly upgraded to allow full energy injection.

For x-ray users a much larger facility is required and DIAMOND has 16 cells with 3 m dispersion-free straights in its 300 m circumference. Very high fluxes extending beyond 30 keV will be available from at least 8 multipole wigglers and soft x-ray users will be served by about 4 high brilliance undulators. A beam emittance of 10-20 nm-rad is conservatively specified and does not represent the ultimate capabilities of the lattice but rather is a compromise adopted for flexibility of operating modes. To extend the output range beyond 50 keV without sacrificing valuable straight section space to high field wigglers the lattice can incorporate superconducting bends (4.5 T) and this has led to the choice of the TBA structure [9] in figure 3 as the most convenient for a progressive upgrade policy of up to one magnet per cell. Installing these mgnets causes an inevitable emittance increase, by a factor of 2 if 8 of the cells are eventually converted.

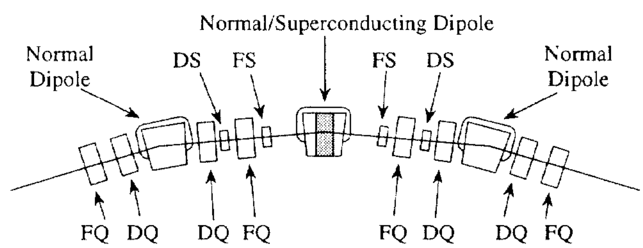

Figure 3. Half TBA Cell in DIAMOND

The ring has comparatively high radiated power losses, especially when it has its full complement of multipole wigglers and superconducting dipoles, so that the 500 MHz RF system has to provide up to 4.5 MV and 500 kW for a 300 mA beam. This may be possible with a pair of 3-cell cavities in a single straight. A full energy booster is likely to be selected as an injector and to be located within the storage ring perimeter.

A site at Daresbury is available and such a choice would allow DIAMOND construction to proceed in parallel with an optimised reduction of resources on the SRS. It is however of considerable concern to the large user community that the period between final SRS closure and DIAMOND availability should be minimised. After a series of positive scientific reviews the case for DIAMOND is now widely accepted and it is hoped that funding decisions will be made quite soon.

5. SLS : A SWISS NATIONAL LIGHT SOURCE

This proposal [11,12] is one of the three that seek to establish light sources at centres without existing facilities of this kind, in this case also in a country with little previous access to synchrotron radiation. However the proposed location, at the Paul Scherrer Institute (PSI) in Villigen, would be able to use the considerable expertise and experience gained on the other accelerator facilities at that site.

A major component of the case for the SLS is to provide a facility for the strong Swiss spectroscopy community and for this reason a design with extremely high brilliance has been chosen. Although the source would be complementary to the ESRF it is also recognised that the volume of Swiss user demand is unlikely to be satisfied by their access rights there if it grows as predicted. The electron beam emittance is so low that the source can provide diffraction limited (ie fully transverse coherent) radiation up to about 100 eV, allowing microscopy and holography applications. In addition a major facility is intended for Swiss industry, particularly for its traditional strengths in precision micromechanics and pharmaceuticals. The higher energy radiation for this purpose would be provided by the bending magnets. For even greater energies the lattice can incorporate superconducting magnets to permit advanced biological structure work. It is envisaged that the SLS would have a number of operating modes, including optimised high brilliance at 1.5 GeV and high flux with enhanced lifetime at 2.1 GeV.

The design of the lattice has placed an emphasis on operational flexibility and the specification also requested inclusion of two 18 m superstraights for future insertion device developments, including long period undulators and possible FEL experiments. The normal straights are also quite long at 7 m and the inclusion of extra quadrupoles allows individual matching of the lattice functions to each planned insertion device. The penalty for this very dense distribution of focussing magnets is that few straights can be made available within a realistic circumference. The chosen solution is a hexagon lattice with 60° arcs and a 240-250 m circumference. The long arcs each have 5 triplet (modified FODO) cells with 10° bends (BNT) and dispersion suppressors (BNF, 5°) to match to the insertion straights as shown in figure 4. Each of the arcs has the possibility to replace the centre bend by a 4.7 T superconducting dipole (BST) but a very low dispersion function at this location minimises the effect of this. This unusual lattice achieves an emittance of only 1.6 nm-rad at 1.5 GeV, confirming [1] that achromatic arc designs should not always be an automatic choice for light sources.

The very high bunch density means that the SLS lifetime is set by Touschek scattering even at its maximum operating energy. Since time resolved experiments will require a few bunches with at least 10 mA in each the 500 MHz RF system must provide adequate momentum acceptance. In fact any increase beyond ± 3 % is not useful because of dynamic aperture limitations and this implies a peak voltage of 2 MV. Four single cell cavities are grouped in one of the straights and fed from two klystrons but this still allows a useful undulator to be included further downstream : this is the only known example of such a sharing feature. In order to control bunch length to achieve either good lifetime or high peak currents it is also proposed to include a higher harmonic cavity.

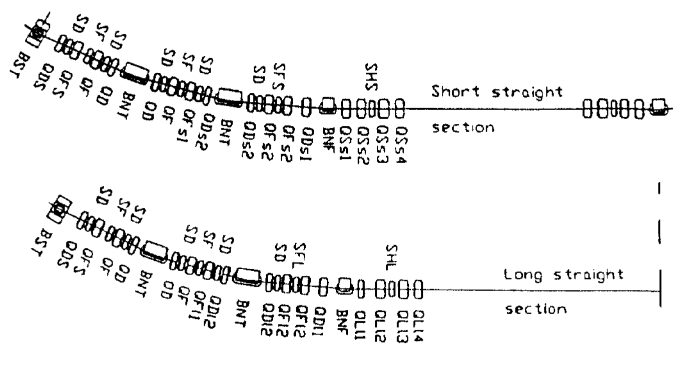

Figure 4. The Hexagon Lattice of the SLS (Half Arcs)

With full energy injection at up to 2.1 GeV much of another straight is taken up with injection components. A conventional scheme using beam stacking will be available but it is also proposed to include a capability for on-axis injection that could be useful if reduced ring apertures are encountered. This will necessitate a very intense injector. Another interesting option under active consideration is a 'top-up' process that could compensate for very poor lifetimes and that would remove the need for normal refills that cause thermal cycling in both ring and beam line components; however it is still unclear if such a scenario is realistic.

If funded the SLS will be directly competitive with the existing European projects ELETTRA, BESSY-2 and MAX-2 as a 3rd generation ultra-high brilliance source, but its superstraights and superconducting dipoles do give it additional potential. Its undulators can cover the full VUV and soft x-ray range, aided by the variable ring energy, and might even extend as far as 10 keV if small gap devices prove to be feasible. The disadvantage of the design is that only 5 insertion straights are available to cover all this energy range, although this still may be well matched to Swiss national needs. The project has now received local approval and serious attempts are in progress to obtain all necessary funding.

6. ROSY : A SOURCE FOR THE DRESDEN REGION

With existing facilities in Berlin (BESSY) and Hamburg (DORIS-3) any new German proposal needs to put forward a particularly strong case. The ROSY project aims to establish a centre for materials research for use by the many institutes in Saxony, to be sited at the Rossendorf Research Centre, and also to encourage industrial applications including radiochemistry and radiopharmaceutical exploitation. This will require provision of x-rays over the range at least 5-18 keV. Funding prospects may be strengthened by the need to invest in this part of Germany.

A high energy ring of 3 GeV has been specified in order to generate hard x-rays from the bending magnets and attempts have been made to produce a particularly economical, compact design [13, 14]. This has involved the development of a novel lattice [15] that extends previous achromatic arc ideas beyond the DBA and TBA. The result is a modified Multiple Bend Achromat (MBA) that generates low emittance in a modest circumference of only 148 m. The lattice has quadrant arcs and 4 accompanying dispersion-free straights of 4.1 m length. As shown in figure 5 there are 3 unit cells in the arcs, each with a simple arrangement of a single 20° bending magnet surrounded by a pair of quadrupoles, and at each end are matching sections with 15° bends, achieved by shortening the magnet lengths at these positions. The matching to the straights is made fully flexible by employing extra quadrupoles, so that both high and low betas can be selected. The reduced bend angle in the outer dipoles decreases their contribution to emittance generation. By inclusion of a field gradient giving vertical focussing in the dipoles, following the ELETTRA and ALS designs, the emittance is reduced further and an impressive figure of 29 nm-rads has been achieved, perhaps a factor 2-3 less than either DBA or TBA designs could have attained in a ring of this size and energy. In a further proposed development it will be possible to replace the central bending element of each arc by a superconducting substitute, applying the same upgrade philosophy as the SLS and DIAMOND, although in this case the need for field gradient will complicate the design.

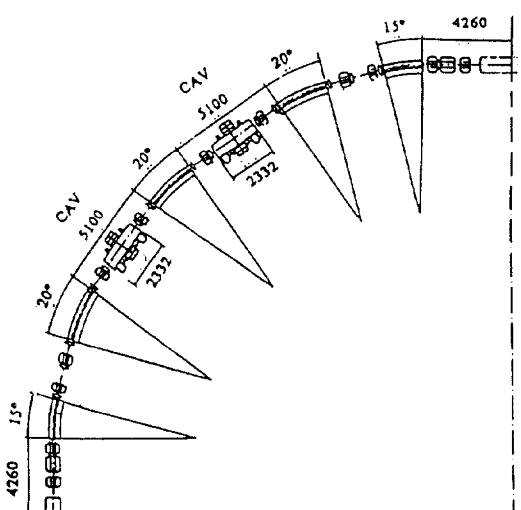

Figure 5. One Quadrant Arc of the ROSY Lattice

This exceptionally compact lattice will be further exploited by including insertion devices in the 3.5 m finite dispersion straights : 4 of these remain for use after allocation of space for injection, RF and diagnostics. With a total of 8 insertions an attractive 23 % of the circumference is able to be exploited for this purpose. The initial design [13] envisaged use of the dispersion-free straights for the high brilliance undulators, although in practice it may be desirable to put the strong (1.5 T) multipole wigglers there to minimise undesirable emittance increases. However this project, like DIAMOND, has emphasised that minimal emittance is not its sole goal and in any event its brilliance is much greater than that at DORIS.

The project team has relied heavily on the experience of other 3rd generation European sources in specifying the principal components. Magnet systems are similar to those on ELETTRA, but the decision not to use full energy injection means ramped main dipoles do suffer some saturation behaviour at peak field due to adopting a relatively high value of 1.4 T. To provide an acceptance of ± 1.5 % the RF must deliver 3.5 MV and this will be supplied by 2 multi-cell LEP cavities at 352 MHz, shown in their quadrant straights in figure 5. The initial beam current specification is a modest 100 mA, requiring only a single 250 kW klystron, but a potential upgrade to 250 mA implies a double window solution on each cavity as adopted at ESRF. The vacuum system will be based on the chamber geometry at HERA. Although the first proposal was to use an 800 MeV linac injector this has now been replaced by a synchrotron fed by a 22 MeV microtron. This booster has a unique design in employing a DBA lattice to produce small beam cross-sections. At the low injection energy the beam lifetime in the storage ring will be limited to about 3 hours, mainly by Touschek scattering.

The status of this project is uncertain but it is certainly an innovative approach to a relatively low budget modern light source of such high energy.

7. CLS : A Catalonian Light Source

The case for a light source to be built in Spain is quite different from those elsewhere, in that Spain has no tradition of accelerator facilities and at present has a relatively small user community, mainly taking beam time at Daresbury and LURE. A previous suggestion had been made in 1991 to include a synchrotron radiation ring in the proposed Tau Charm Factory complex at Seville, using the available positron injector. Since then a more comprehensive feasibility study has recommended construction of a light source at a site in the Vallès area close to Barcelona, a Catalonian initiative aimed at users from Spain, Portugal and perhaps Southern France. Spain is a member of ESRF but wishes to complement this with some national facilities as do other major European participants. The scientific case is based largely on materials science and structural biology and this therefore implies a high energy ring. Of equal importance is the technology transfer to Spanish industry and the creation and training of a community of accelerator and instrumentation specialists. It is believed that such a project would improve the participation of Spain in ESRF and CERN, including both scientific exploitation and contract placements in Spanish industry.

A preliminary set of parameters includes an energy of 2.5 GeV and a beam current of 200-300 mA. A 12-cell DBA lattice of 250 m would provide straights of 4 m and emittance in the 15-30 nm-rad region. With 8 or 9 insertion devices and a similar number of bending magnet ports a large facility is envisaged. The selected 1.5 T bending field provides useful radiation up to about 20 keV.

A 200 MeV linac would feed a 1 GeV booster synchrotron situated within the storage ring perimeter. It is possible that this booster would also be used by the existing HEP community at Barcelona for experiments such as detector calibration, although experience elsewhere has demonstrated that this can rarely be a satisfactory conjunction. Full energy injection will also be considered.

The project is being guided by the Autonomous University of Barcelona which has also offered the site. Further design studies are being undertaken by staff seconded to overseas laboratories during a necessary training period. It is considered essential that eventual construction must be carried out by local Spanish industry. Funding is being sought from both federal and local bodies.

8. ISI-800 : A COMPACT SOURCE FOR THE UKRAINE

The Kharkov Institute of Physics and Technology in Kiev had made an earlier proposal [3] to use a 3 GeV pulse stretcher ring in a low emittance mode as a light source operating between 700 MeV and 2.5 GeV, but in the last year this has been replaced by a proposed small, dedicated VUV ring called ISI-800 [16]. This is to form the basis of a Ukrainian Synchrotron Radiation Centre. The 800 MeV ring is only 47 m circumference and its 4 TBA cells generate an emittance of about 25 nm-rads. The simple lattice uses a field index in the dipoles (n=3) and doublets to match to the 3.2 m straights. A 700 MHz RF system has been selected and the Touschek limited lifetime is in the range 3-6 hours at the 200 mA design current. The status of this project is unknown.

9. CONCLUSIONS

In assessing these proposals a number of conclusions are clear. There is a very great demand for access to synchrotron light sources that still exceeds the supply despite the considerable number of facilities already in existence or under construction in Europe. The ESRF has a vital role but no national user community believes it can satisfy more than a fraction of their needs, whether because they require lower energy optimised photon output or because the volume of experiments exceeds their share of ESRF capabilities. All countries with major user communities have concluded that they must have one or more advanced national facilities.

Most new projects have concentrated on solutions that increase the source brilliance, although these produce large, expensive facilities. In the last decade the DBA and TBA solutions have become predominant but alternatives are included in these proposals and for example zero dispersion straights are no longer assumed automatically to be essential. More variety is also being pursued with the interest in superstraights and bypasses and several of the new proposals are now also assessing the progressive replacement of normal by superconducting dipoles.

With the increasing emphasis on industrial applications and the ever widening list of other uses of synchrotron radiation most of the proposals are prepared to accept some reduction in brilliance in order to increase fluxes or operating flexibilities. Time resolved experiments are becoming more important and the rings must be able to operate with a few intense bunches but with reasonable lifetimes. Only the SLS project attempts to extend existing 3rd generation solutions towards 4th generation concepts of ultra low emittance and short bunches.

Both the French and UK proposals for replacement x-ray sources seem likely eventually to be funded but the fate of the others is less clear, depending on the political will to create new facilities where none previously existed. What seems almost certain is that at least one project will be funded before EPAC-96 and that further changes in design proposals are inevitable by then. One obvious omission at present is an advanced European VUV ring to replace SuperACO when that eventually closes : only SINBAD has been proposed and the UK seeks a major partner before it can proceed.

10. ACKNOWLEDGEMENTS

I am indebted to members of the various design teams for helpful information, in particular M-P Level, W Joho, D Einfeld and J Bordas.

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