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OPERATING EXPERIENCE WITH EXISTING LIGHT SOURCES

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It is instructive to consider what an explosive growth there has been in the development of light sources using synchrotron radiation. This is well illustrated by the list of facilities given in Table I. In many cases, synchrotron light facilities have been obtained by tacking on parasitic beam lines to rings that were built for high energy physics. Of the twenty-three facilities in this table, however, eleven were built explicitely for this synchrotron radiation. Another seven have by now been converted for use as dedicated facilities leaving only five that share time with high energy physics. These five parasitically operated facilities are still among our best sources of hard x-rays, however, and their importance to the fields of science where these x-rays are needed must be emphasized.

While the number of facilities in this table is impressive, it is even more impressive to add up the total number of user beam lines. Most of these rings are absolutely surrounded by beam lines and finding real estate on the experimental floor of one of these facilities for adding a new experiment looks about as practical as adding a farm in the middle of Manhattan. Nonetheless, the managers of these rings seem to have an attitude of "always room for one more" and new experimental beam lines do appear. This situation is necessary because the demand for beam time has exploded at an even faster rate than the development of the facilities. The field is not only growing, it can be expected to continue to grow for some time. Some of the explicit plans for future development will be discussed in the companion paper by Lee Teng.

Table I. Operating Synchrotron Radiation Facilities

	Energy GeV	Current ma	Lifetime hours	Emittances m-rad x 10^{-}	Number of Beam Lines	Number of Insertion Device
France						
ACO, Orsay	0.54	200	5	12	4	1
DCI, Orsay	1.8	300	>30	130	3	0
United Kingdom						
SRS, Daresbury	2.0	300	10	1 x 150	8	2
Germany						
Hasylab, (Doris), Hamburg	3.7	90	6	27 hor	25	1
BESSY, W. Berlin	0.755	600	3	1.5 x8	26	0
Italy						
ADONE, Frascati	1.5	150	6	23	6	1
Japan						
PF, (KEK), Tsukuba	2.5	150	18	6.5 x 54	25	2
SOR-Ring, Tokyo	0.38	250	3	30 hor	5	0
UVSOR, Okasaki	0.600	200	2	0.8 x 8		2
TERAS, Tsukuba	0.6	100	4	?	10	0
USA						
SURF(NBS), Gaithersberg, MD	.284	100	0.5	large	11	0
CHESS(Cornell), Ithaca, NY	4.7-5.6	75	3	18	4	1
SSRL (SPEAR), Palo Alto, CA	3.5	100	>10	46	18	4
Tantalus(SRC), Stoughton, WI	0.24	200	4.3	140	8	0
Aladdin(SRC), Stoughton, WI	0.8	20	1.4	4 x 12	1	0
NSLS-VUV(BNL), Upton, NY	0.75	300	2.0	0.1 x 14	13	1
NSLS-XRAY(BNL), Upton, NY	2.4	60	2.5	0.3 x 10	13	0
USSR						
VEPP-2M, Novosibirsk	0.67	500	?	?	?	?
VEPP-3, Novosibirsk	2.0	?	?	?	?	?
VEPP-4, Novosibirsk	5.0	?	?	?	?	?
Siberia 1(IAE), Moscow	0.4	100	?	?	?	?
Yerevan	5.0	?	?	?	?	?
Pachra	1.2	?	?	?	?	?

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Figure 1 shows another illustration of the growth of this field. In this figure we show the number of synchrotron radiation related papers contributed to this sequence of conferences dating back to the beginning in 1965. A rather arbitrary selection scheme was used to decide which papers belong in the numbers used for this graph. In any case, the graph clearly illustrates how the field of activity has developed in a short span of twenty years.

A few highlights of the operation of these various machines should be mentioned. (The items selected reflect the author's prejudices; clearly many other equally important contributions could be listed.) The SRS at Daresbury and the Photon Factory (PF) at KEK have now had a couple of years of operation as the first successful machines built as dedicated facilities for generating photons in the hard x-ray range. These machines have achieved currents of hundreds of milliamperes and multihour lifetimes. The x-ray ring of NSLS at Brookhaven is now also coming into operation. This machine has not yet achieved the currents and lifetimes that are ultimately expected, but the small emittances that are supposed to be a feature of this machine appear to be realized, and a vigorous research program can now begin there. In the VUV region, the NSLS machine has been supporting a large research program for about two years. We will hear later in this session about the very successful operation of another machine in the same general VUV parameter range, BESSY in West Berlin. This machine is characterized by an excellent level of engineering; their fault reports for one year in their annual report [1] are all on one page! This is the only machine the author has ever seen that runs without operators in the control room. We will also hear in this session about the excellent work on undulator harmonic production at ACO in Orsay.[2] The Orsay group must surely also hold the lifetime record with observation of sixty hours lifetime for a high current positron beam in DCI. It must be nice to start an experiment on Monday and still be taking data on the same fill on Thursday. We have never had reports to these conferences on the work being done in the USSR on synchrotron radiation. We know, however, that a number of interesting programs are in place.[3] The VEPP-2M and VEPP 3 machines at Novosibirsk are now completely dedicated to synchrotron radiation research. The VEPP 3 machine, in particular, has parameters which make it quite comparable to the SRS, PF and NSLS-x-ray rings. It, indeed, supports research programs of about forty groups from all regions of the Soviet Union. Like its counterparts in other parts of the world, the facility supports research ranging over all subjects from solid state physics to the bio-chemico-physical problem of how muscle tissue converts chemical energy into mechanical energy. VEPP 4 is still primarily used for colliding beam physics but x-rays from special beam crossing dipoles are available with energies up to 100 kev.

Mention has been made of the low emittance of the NSLS X-ray ring. In fact, if one looks at the emittance column of the table, one notices that both of the NSLS rings have very low emittances compared with other rings in the comparable energy and current regions. These machines were designed with the special lattices required to generate the low emittance and high brightness photon beams as developed at Brookhaven by G. K. Green and Rena Chasman. The high brightness features of these lattices have been realized as designed. The VUV ring has, indeed, been operating now for nearly three years with these high brightness beams and has been supporting a very extensive research program. The high brightness has permitted some of the beam lines to develop resolutions that are not available at other sources. It is very important for future machines to know that such high brightness sources work as designed.

There have been a number of interesting problems associated with the operation of these facilities. Most groups operating these machines will agree that the vacuum system is the most difficult technological part of the machine. The problem is that the synchrotron radiation causes gas desorbtion on the walls. The Coulomb scattering or Bremsstrahlung from the desorbed gas then may limit the beam lifetime. Assuming that the system remains leak tight and that reasonable pumping speed is in place, then one expects that the ring will condition; i.e., the synchrotron radiation scrubs the wall until it is free of desorbable gases. It is important to

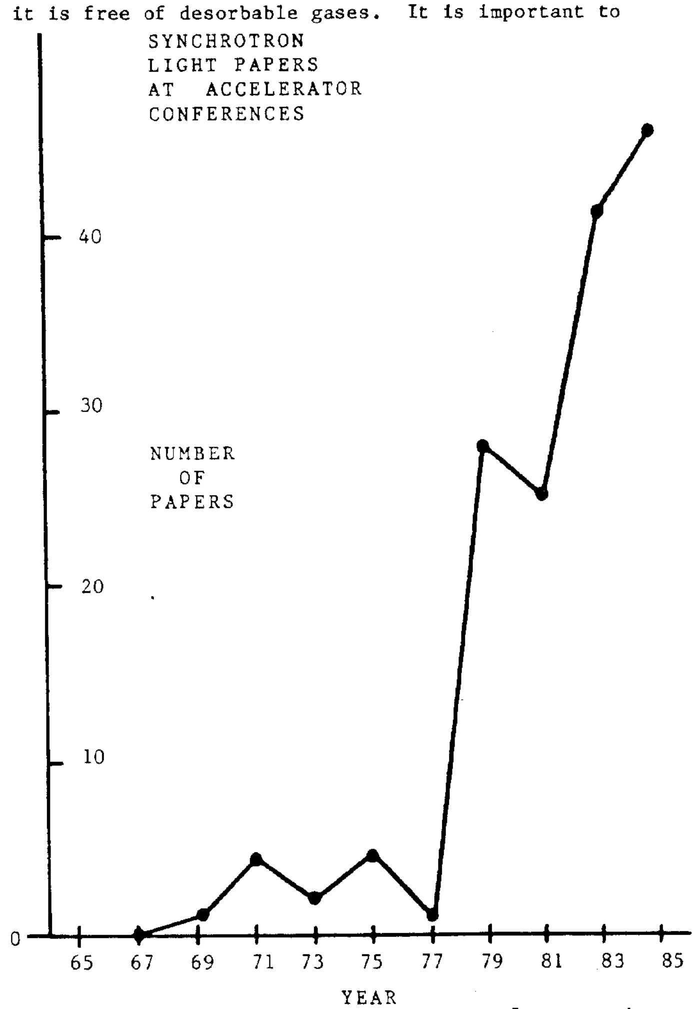

Fig. 1. This graph shows the number of papers about synchrotron radiation or about accelerator technology coming from synchrotron radiation facilities published in the proceedings of the Particle Accelerator Conference.

recognize at this point the importance of an adequate injection system, particularly if one is to rely on beam cleaning for a significant parts of the vacuum chamber treatment. Otherwise, one can get caught up in the dilemma that one cannot get much beam because the vacuum is not good enough and one cannot improve the vacuum because there is not enough beam. This was a significant part of the commissioning problem at the NSLS x-ray ring, for example. We had a very low charging rate in that machine and the injection energy is low enough that the Coulomb scattering lifetime at the rather high pressure limited the current to a few milliamperes. Under these conditions, it was not clear that the ring was conditioning at all. After a better bakeout of the chamber, making sure the system was leak tight, and some modest improvement in the charging rate, we began to see steady improvement; lower pressure and longer lifetime. This dilemma was not anticipated by watching the performance of the high energy colliding beam machines. All of those machines of necessity have injectors capable of high charging rates because they have to be potent enough to make copius numbers of positrons. Even with a high current injector, the beam cleaning process may be too slow. This emphasizes the importance of starting with the system as clean as possible and with adequate pumping speed. At the Photon Factory, for example, it appeared from the initial running period that an unacceptable time was going to be required to condition the chamber. They stopped operation and did a glow discharge cleaning of the chamber with an immediate gain of more than an order of magnitude in lifetime. Not only did they achieve better vacuum, they speeded up the rate of additional conditioning. The first results of this process were reported in their paper at the Santa Fe conference [4] and more recent details are available in the literature.

One of the difficult aspects of the vacuum system is the complexity. In most cases, the chamber must be water cooled in any area that can be hit by the radiation. Then the beamlines have to be connected usually without windows. It is like living under the sword of Damacles to try to operate the machine with twenty or more beam lines tied in to such a fragile system. Nearly every group can recite a few hair-raising tales of accidents or near misses. Fortunately, venting such a system to air does not ordinarily contaminate a system as bad as a new uncleaned system. Usually a bakeout suffices to restore the system to a state where it can be conditioned readily. Controlled venting with pure nitrogen seems to cause negligible contamination.

Once the first order problems of the vacuum are solved, then one begins to notice the problems associated with ion trapping. This effect is as old as the electron storage ring concept; this author is old enough to remember problems with ion trapping in the MURA FFAG models, the Princeton-Stanford experiment and the ADA [5] storage ring at Orsay back in the 60's. The problem is still with us. Off hand one might expect that in a bunched beam, the ions would escape between bunches. A simple model can be constructed of the periodic focusing force of the electron bunches and one finds that, instead, trapping can occur.[6] The heaviest species are the easiest to trap. With a significant amount of trapping, the space charge of the ions blows up the beam and, it turns out, allows trapping of lighter species which may be more prevalent in the gas. This can be an almost avalanche effect and the combination of scattering from ions and the non-linear lens action of the ion space charge can cause poor lifetime. It is not always clear, by the way, that the ion trapping is all bad. If it causes some beam size growth without actually limiting the lifetime, and if the experimental program can tolerate the larger beam size, then ions may be helpful for reducing or eliminating instabilities. Much of the high current operation at BESSY has exploited this feature [7] and it has occasionally been used in the same way at the NSLS-VUV ring. In most cases, however, ion trapping is considered undesirable and the question is how to avoid it. In the first place, ordinary vacuum improvement also alleviates the ion trapping and its effects. To remove it completely, however, requires more drastic treatment. One of the oldest methods consists of using clearing electrodes. This method is still helpful in a number of rings, e.g., SRS has clearing electrode plates in the dipoles which cover 50% of the ring circumference and in PF the glow discharge wires can be used as clearing electrodes. The recent experiments at Aladdin are particularly interesting.[8] In that case, the ion trapping has posed a very serious limit to the current that can be injected because of the combination of very low injection energy, slow damping rate, slow filling rate, and poor vacuum. They are caught in the same dilemma that bothered the NSLS x-ray ring but aggravated particularly by ion trapping. In theAladdin case, the tune spread caused by the ions is large compared to the spacing of low order resonances. Recent improvements in the clearing electrodes have alleviated this situation somewhat and the current has been pushed up to 30 ma. More clearing will be added. The most dramatic way to rid a machine of ion trapping is to use positrons instead of electrons. This choice has been strongly emphasized by the Orsay group and the spectacular lifetime achieved in DCI is a strong testimonial to their opinions.[9] They have exceptionally long lifetimes with electrons, too, but with positrons they do not see the erratic dropouts that all of us associate with ion trapping and their EXAFS users report better resolution. Recent experiments at SSRL have also indicated the advantages of positrons and they have plans to convert SPEAR to run with positrons for SSRLS operations.[10]

Once all of the vacuum problems are solved and assuming all of the usual hardware construction has been properly done, then one begins to see the real limitations on the performance of the storage rings. These are, of course, instabilities. Light source storage rings have all of the instability problems known to our friends in the colliding beam business (except the beam-beam interaction) plus a few of our own. Colliding beam machines typically operate with one or, at most, a very few bunches. In most cases synchrotron light sources prefer to run with all bunches full. Under these conditions, the performance may be limited by coupled bunch instabilities in either the longitudinal or one of the transverse planes. The vertical motion can be particularly sensitive. In the colliding beam machine, the vertical emittance is typically blown up deliberately by horizontal-vertical coupling because the beam-beam interaction is reduced by that technique. In the light source we like to reduce the coupling to a very small number to optimize the brightness. There is then virtually no Landau damping of the vertical motion. The first line of defense is to try to keep coupling impedances as low as possible. Usually the culprits are higher order modes in the rf cavities. In some cases these can be damped or their frequencies shifted so that they do not excite unstable modes. In other cases this is not possible. Feedback has been successfully used at NSLS-VUV to stabilize coupled longitudinal modes and permits three bunch operation. More channels are under development to permit operation with all nine bunches. Feedback will also be tried to stabilize transverse modes. In the absence of such feedback, it is necessary at NSLS-VUV either to enlarge deliberately the beam with the skew quadrupole coupling or to introduce more chromaticity with the sextupoles. The first choice is undesirable because it reduces the beam brightness; the second choice appears to reduce the lifetime because the strong sextupoles reduce the dynamic aperture. At BESSY they have two rf systems;one at 500 Mhz and one at 62.5 Mhz. They have tried to stabilize coupled bunch instabilities of bunches trapped in the high frequency system by introducing synchrotron tune spread among the bunches using the low frequency system. This has not been successful presumably because of insufficient amplitude in the low frequency system. They have had more success trapping the beam in the low frequency system then stabilizing it by introducing Landau damping within the bunches by using the high frequency system to create waveform distortion. A tune splitting cavity has been installed in the NSLS-VUV ring and will be tried in the future. As mentioned above, BESSY has used the stabilizing effect of ion trapping to limit the effects of instabilities. At SRS, this effect has also been used along with octupoles which introduce some controlled Landau damping. They still see the instabilities at injection energy but their amplitudes are restricted to small enough values that no beam is lost. As the beam is accelerated, the instabilities disappear and the octupoles are no longer needed.

Another problem is orbit position stability which has more severe requirements than for other accelerator applications. It has been necessary at SSRL and Hasylab,[11] for example, to use dynamic feedback based on actual detectors of the x-ray spot positions. This is straightforward in principle but can be difficult in practice to avoid coupling among the many beam lines.

We must also mention that a large number of the machines in operation have begun to utilize wigglers and undulators to generate special spectral features. These have been generally successful and the problems of incorporating them into the machine lattices have turned out to be tractable. This bodes well for future operation of such devices in existing machines as well as for new machines which will be especially designed to exploit such sources.

The author hopes that some of the challenge and the excitement of this branch of accelerator development can be grasped from these short comments. He wishes to thank directors and staff of a number of facilities who have kindly provided information which has been included, and he wishes to apologize for many equally interestisng items that were not included because of limits of time and space.

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[1] Jahresbericht 1984, BESSY, Lentzeallee 100, 1000 Berlin 33.

[2] J. Ortega, et al, Coherent XUV harmonic production, this conference. Also see B. Girard, et al, Optical Frequency Multiplication by an Optical Klystron, Physical Review Letters, 17 December 1984, Vol. 53, No. 25.

[3] The table entries for the USSR and the comments here are taken from the author's notes from a talk given at BNL by Dr. Sergei Kapitsa.

[4] Photon Factory: Status of Storage Ring, IEEE Transactions on Nuclear Science, Vol. NS-30, Number 4, p. 3130, August 1983.

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[7] G. Mühlhaupt, private communication.

[8] E. Rowe, private communication.

[9] E. Sommer, private communication.

[10] H. Winick, private communication.

[11] C. Kunz, private communication.