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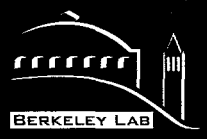

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Improving and Extending Performance at Synchrotron Radiation Facilities

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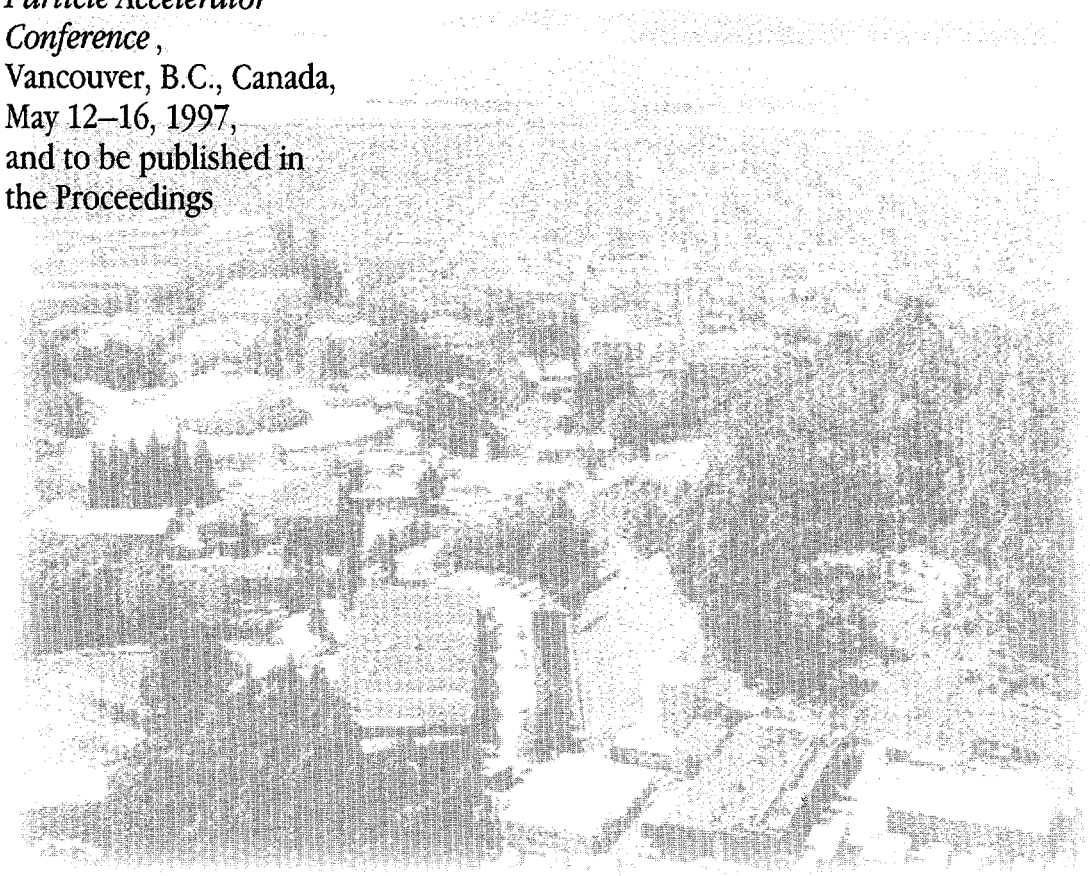

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DISCLAIMER

IMPROVING AND EXTENDING PERFORMANCE AT SYNCHROTRON RADIATION FACILITIES *

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Synchrotron radiation facilities around the world have now matured through three generations. The latest facilities have all met or exceeded their design specifications and are learning how to cope with the ever more demanding requests of the user community, especially concerning beam stability. The older facilities remain competitive by extending the unique features of their design, and by developing novel insertion devices. In this paper we survey the beam characteristics achieved at third-generation sources and explore the improvements made at earlier generation facilities.

I. INTRODUCTION

Dedicated synchrotron radiation user facilities have been part of the global research landscape for more than thirty years. Some of the more venerable ones, like SSRL in the USA. the SRS in the UK, HASYLAB in Germany, and the Photon Factory in Japan (to name but a few), continue to produce forefront scientific results. In order to maintain their competitiveness, most of the older facilities have graduated through a series of upgrades; for example, by increasing beam energy ranges and current capabilities, reducing beam emittances, incorporating novel insertion devices, and so on. The more recent facilities based on the so-called third-generation light sources face different challenges. The expectations of these machines were initially downgraded from their linear-model design values because of uncertainties related to intra-beam scattering, momentum acceptance, single- and multi-bunch instabilities, and dynamic aperture. However, the new machines soon attained beam parameters that are very close to the linear-model predictions. Users quickly learned to utilize the higher brightness photon beams, and now beam stability, on the scale of microns, over time scales from milli-seconds to many hours, are being demanded – and met.

The content of this paper is compiled from information provided to the author from existing facilities. I have attempted to be faithful to that information, and apologize for any discrepancies that may have crept in through poor interpretation or (more likely) insufficient research on my part.

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II. THREE GENERATIONS OF SYNCHROTRON LIGHT SOURCES

Synchrotron light sources have been arbitrarily divided into three generations. The first is meant to describe facilities that were parasitic on machines that were built for a different purpose – high energy physics (HEP). Examples of such facilities are Tantalus (Wisconsin, U.S.A.), and DCI (Paris, France). "Second-generation" describes accelerators that were purpose-built as dedicated synchrotron radiation facilities, such as the SRS (Daresbury, UK), and the Photon Factory (Tsukuba, Japan). The third-generation sources are also dedicated facilities, but designed to give orders of magnitude more photon beam brightness by taking advantage of the development of long undulators. Requirements of these machines include long straight sections, typically 6 m or more between magnets, and low emittance beams, typically less than 10 nm-rad.

Unfortunately, many machines do not fit nicely into these categories! For example, SSRL (Stanford, USA), is based on the SPEAR storage ring, which was built as a colliding beam facility for HEP, placing it squarely into the first generation. However, SSRL developed into a dedicated facility, SPEAR has some very long straight sections, and SSRL has pioneered the utilization of wigglers and undulators, which surely raises it's "status" to at least second generation. Similarly, Super-ACO (Paris, France), and NSLS (Brookhaven, U.S.A.), have many undulator beamlines, albeit from somewhat shorter straight sections, utilizing beams with emittances somewhat larger than those defined above! So where do they fit? We will not pursue this question further. Arbitrarily, we will call the "new" facilities those that include the ESRF (Grenoble, France), and the other "third-generation" designed sources that were built thereafter – all others are "older".

III. PERFORMANCE AT THE OLDER FACILITIES

Almost all the older facilities have upgraded their capabilities since they were first commissioned. Those described below should be regarded as representative, since it is impossible, in a paper of this length, to list all the improvements that have been made to all the facilities throughout the world.

(a) Stanford Synchrotron Radiation Laboratory (SSRL) is a dedicated facility based on the former e^+e^- colliding beam storage ring SPEAR. This facility has gone through several upgrades: First the lattice was changed to eliminate the collision optics (mini-β_y), used in the HEP program, and to reduce the natural emittance from 0.47 μm-rad (at 3.0 GeV) to 0.13 μm-rad [1]. In the process, the chromaticity correction scheme was modified to give a larger dynamic aperture. An associated benefit to eliminating the mini-β sections was a significant reduction in quadrupole strengths in the straight sections which, in turn, led to a reduction in a diurnal variation in the global closed-orbit. The closed-orbit stability has been improved further (by a factor of ≈ 5) by a global feedback system that operates in both planes, and a local system that operates for particular beamlines in the vertical plane. The net result is an orbit stability of around 100 μm (horizontal) by 80 μm (vertically). The facility has built a dedicated injection system (linac and booster synchrotron), so that SSRL operations are essentially independent of SLAC operations. Currently, SSRL operates with 2, 8-pole electromagnetic wigglers; 3 permanent magnet hybrid wigglers, and an elliptical polarizing undulator. Future upgrade plans include full energy (3 GeV) injection, and a major lattice rebuild to further reduce the emittance.

(b) The Synchrotron Radiation Source (SRS) was the first of the purpose-built synchrotron radiation facilities for the utilization of x-rays. This facility was designed in 1974, before the impact of undulators, and the requirement for low emittance, was recognized. In fact the "emittance" (at ≈ 0.5 μm-rad at 2 GeV) is not even mentioned in the 1975 design report – though it is implicitly included in the calculated beam sizes. The SRS was, and still is a generator of flux, rather than brightness. Soon after it's inauguration in 1981, a 5 T superconducting wiggler was added to the lattice that pushed the radiation spectrum to a critical energy of ≈ 16 keV. This was soon followed by an undulator. In 1987 a lattice rebuild was instituted that doubled the periodicity of the FODO lattice structure, and reduced the emittance to 0.1 μm-rad, significantly improving the performance of the undulator, and the flux that could be focused onto small samples, for example in protein crystallography experiments. Recently a second wiggler with a peak field of 6 T was added. Together, these three insertion devices service 15 user stations, for a total of 40. However, this is far from the end of the story. Despite having filled all the space around the circumference, the SRS has embarked on a scheme [2] to relocate accelerator components around the ring (including all four accelerating cavities) in order to free up space for two new multi-pole wigglers – each 1.2 m long, with 10 poles, producing a maximum field of 2 T. This funded project extends the useful life of the SRS well into the next millennium! The Daresbury Laboratory also has a fully developed proposal, not yet funded, for a third-generation x-ray source called DIAMOND [3].

(c) Following closely on the heals of the SRS, came the Photon Factory (PF) which has parameters very similar to the SRS (energy = 2.5 GeV, emittance = 0.13 μm-rad). Over the past 15 years the main upgrades to the facility have been in the development of undulators, with many novel concepts being designed, built, and implemented for users. Currently there are six insertion devices in the ring, one of which – "the revolver" – has 4 separate undulators capable of serving one beam line, two that operate in either wiggler or undulator modes, and one that can provide elliptically polarized radiation. Right now the PF is in the middle of a long shut down for an extensive lattice refit that will push the beam emittance down to 27 nm-rad, and increase the photon brightness from it's many undulator sources by an order of magnitude [4]. Prior to this shutdown, the PF replaced two RF cavities with ones designed to damp higher-order cavity modes (See Figure 1). With these cavities in operation, no serious beam instabilities were observed during normal (400 mA) multi-bunch operation. So, on the last shift before the shut down, the current was pushed, without instability problems being observed, until the RF tripped on a reverse power interlock, at a current of 773 mA. The PF looks forward to bringing the accelerators back into operation for users sometime this autumn.

Acceleration frequency(MHz)	*500.0*
Shunt imedance(MΩ)	*6.8*
Unloaded Q-value	*39,000*

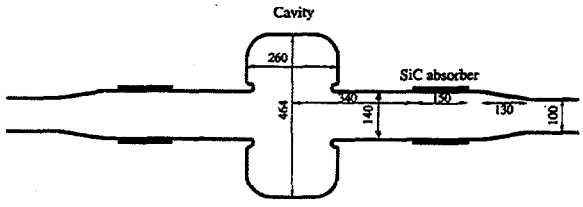

Figure 1. HOM-Damped Cavity for the PF

(d) A unique feature of the BESSY facility, in Berlin, is it's utilization by the Physikalisch-Technische Bundesanstalt (PTB) as a primary radiation source standard in the VUV and soft x-ray range of the electromagnetic spectrum. This requires a precise knowledge of many machine parameters, in particular the electron energy. To this end, the accelerator physicists at BESSY have developed and implemented two techniques for measuring the energy, one based on resonant depolarization, the other on Compton back-scattering of laser photons [5] (See Figure 2). The latter has been used to measure not only the beam energy (to an accuracy of ≈ $1{:}10^4$), but also the energy spread, and the momentum compaction factor.

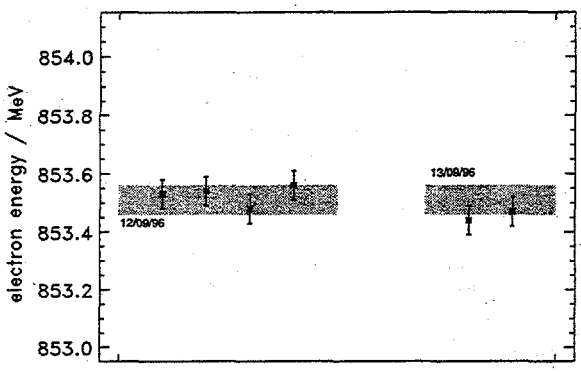

Figure 2. Electron energy measured by resonant spin depolarization (■) and by Compton back scattering

(e) The Aladdin facility, in Wisconsin, was originally conceived as an 800 MeV facility, but now operates for one-third of it's time; i.e., 8 hours/day, at 1 GeV. The facility has 29 beamlines, including one undulator line. Six bend magnet beamlines are dedicated for x-ray lithography, a program that has seen tremendous growth at the facility, and one beamline to the emerging technology of micro-machining. In the immediate future, two new undulators and their beamlines will be commissioned, to be followed by a high resolution beamline being financed by Canadian institutions. An electromagnetic undulator has been built and is at the field mapping stage, to be installed at the end of the year. Active accelerator tuning, including quadrupoles and steering magnets, will be implemented with the new undulators, to maintain tune and orbit stability as the undulators are manipulated by the users. The global orbit feedback system currently in use maintains the closed-orbit to within ± 5 μm against slow (< 0.2 Hz) perturbations.

(f) The Super-ACO facility, in Paris, is based on an 800 MeV, 39 nm-rad emittance positron storage ring that has eight 3.5 m long straight sections. The alternate straights have zero and 1 m dispersion. The facility operates 23 beamlines, with 4 undulator sources, an asymmetric hybrid wiggler, and has the only ring-based FEL facility in the world that is routinely operated for users [6]. The ring is also routinely operated in a "two-bunch" mode, where each bunch is filled to 120 mA, and the beam lifetime is reduced by only a factor of two (to ≈ 3 hr) from the nominal 400 mA 24-bunch operation. A recent upgrade replaced the old 100 MHz cavities with 500 MHz designs, which will lead to shorter bunches for the timing experiments, and increase the FEL gain. SuperACO is also one of the few rings that is filled directly from a linac, that can produce either electrons or positrons at the full operating energy. This made it an ideal facility to study the "sudden micro beam-loss" phenomenon that plagued many electron accelerator facilities in the eighties. The accelerator physicists were able to show that the effect was due to the trapping of photo-ionized dust particles in the vacuum chamber – thereby ending years of debate as to the mechanism of this difficult-to-study effect.

(g) The National Synchrontron Light Source (NSLS), on Long Island, operates two storage rings at it's facility, the 800 MeV VUV ring, and the 2.5 GeV X-Ray ring. Here we will concentrate on the X-Ray ring, which has eight zero-dispersion straight sections, each 4.5 m long, and an emittance of 0.1 μm-rad. The major improvements in accelerator operations include a dramatic reduction in the vertical emittance, from 2 nm-rad (i.e., an emittance ratio of only 2%) down to 0.1 nm-rad, a value comparable to those found at third-generation sources. Tests have also been successful in reducing the natural emittance to 45 nm-rad; this will become the routine operating option once improvements to the analog global-orbit feedback system have been implemented. Other improvements include increases in energy (to 2.6 GeV), current (from 200 to 450 mA), and beam stability. The latter has benefited from an increase in the number of beam position monitors (BPMs) by a factor of two (to 16). This enabled the analog vertical closed-orbit feedback system to utilize 8, rather than 6, harmonics in the correction algorithm, and improved the long-term vertical orbit stability by a factor of 3 – down to about 3 μm (See Figure 3). Similarly, drift in the horizontal closed orbit has been reduced to around 2 μm, by using both harmonic feedback and a newly developed digital system. Unfortunately, this correction is with respect to the BPMs, which are not stable themselves to this accuracy. With the improved vertical emittance and beam stability, comes the opportunity to investigate small gap insertion devices. This work started in 1994 with the installation of a variable aperture vacuum chamber and small period undulator [7], and a report on the more recent developments is given in these proceedings [8].

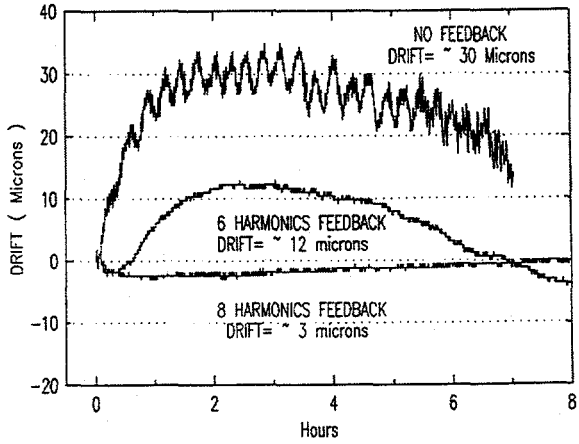

Figure 3. Stabilization of the vertical orbit in the NSLS X-Ray Ring using the harmonic correction algorithm

IV. PERFORMANCE OF THE THIRD-GENERATION LIGHT SOURCES

The third-generation sources are divided into two broad categories: the lower energy storage rings (≈ 2 GeV) optimized to produce high brightness beams in the VUV and soft x-ray regions of the spectrum, and the higher energy rings (around 7 GeV) optimized for harder x-rays. Currently there are 5 low energy operational facilities (ALS, SRRC, ELETTRA, PLS, and MAX-II) with many more in the construction or design phases; and 3 high energy rings operational, or soon to be operational (ESRF, APS, and SPRING-8). The first of the new sources, ESRF, was commissioned in 1992. These facilities have benefited greatly from the lessons learned at the older facilities, and as a consequence reached their design goals soon after start-up. How then has the performance of these machines been improved and extended?

In all cases the first response has been in beam motion stabilization – in the frequency range from dc to synchrotron and betatron oscillation frequencies. The requirements on beam motion are typically quoted as a fraction, in the range 5-10%, of the beam size. With vertical beam sizes reaching the level of 10 μm, this implies beam stability at the level of ≈ 1 μm – a very severe constraint to provide over periods of many hours.

The faster motion, introduced by instabilities driven by vacuum chamber and cavity impedances have been cured via several different avenues: tuning of the higher-order modes in the cavities; utilizing bunch fill patterns that induce frequency differences from bunch-to-bunch; and by utilizing feedback. Slower motion, caused by ground motion, temperature changes, residual fields in undulator magnets, etc., has been either eliminated at the source [9], or through feedback systems. By these means, beam stability has been brought under control at all the operational facilities, to the stringent levels demanded by the users.

At the ESRF, other improvements have been implemented. The current has been increased from 100 to 200 mA, the natural emittance has been reduced from 7 to 4 nm-rad, the emittance coupling reduced from 10% to below 1%, and the vertical beta function reduced to better match the electron emittance aspect ratio to the photon emittance. Together, these improvements have increased the brightness of the undulator radiation from the original specification of 5×10^{17} photons/(sec.mm^2.mrad^2.0.1% bandwidth) to a value of over 10^{20} – an improvement of more than two orders of magnitude in brightness [10] (See Figure 4). And there are plans to extend this yet further – not bad for a machine that is only in it's fifth year of operation.

The other facilities have also increased their beam brightness' over those originally quoted, mainly by achieving the natural beam emittances expected from simulations, and like the ESRF, operating with lower emittance coupling. However, in the case of the lower energy storage rings, reduced vertical emittance is offset by the reduction in beam lifetime, caused by the Touschek effect, so the gains are not as apparent.

The ALS also has a proposal to upgrade three of the 36 lattice bend magnet with short superconducting magnets operating at up to 5 T. This could provide white light x-ray beams to as many as 18 user hutches.

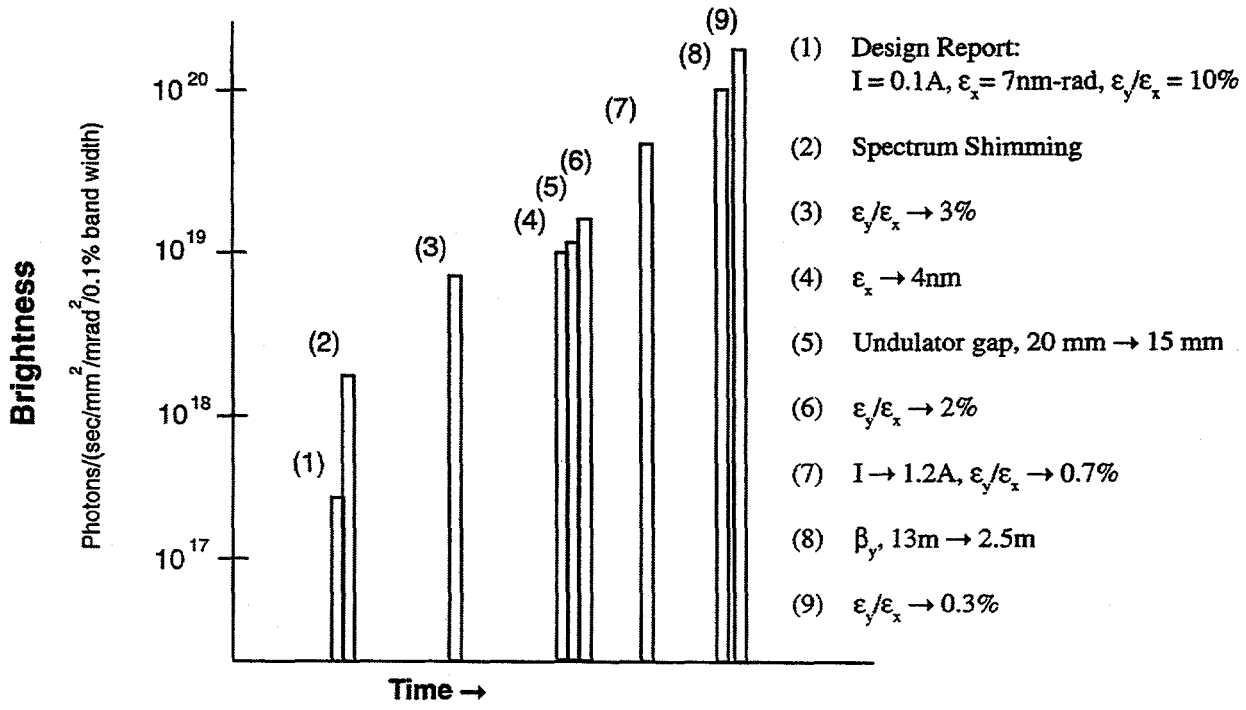

Figure 4. Improvements in ESRF Brightness from 1992 to Present

V. SUMMARY

Over the past few decades, synchrotron radiation facilities around the world have accumulated a well deserved reputation for producing high quality science from accelerators that have been almost continually upgraded. The third-generation facilities owe much to their predecessors in understanding the dynamics of tightly focused electron beams, their interactions with their environment, and in developing the technologies necessary to generate the extremely bright beams of radiation being demanded by the user community. They, in turn, are taking this knowledge base yet further, in order to improve their own performance and to provide guidance for the next generation of facilities. The future of synchrotron radiation is indeed bright – and getting brighter.

VI. REFERENCES

[1] J. Safranek and H. Wiedemann, "Low-Emittance in SPEAR", 1991 IEEE Particle Accelerator Conference, San Francisco.

[2] J.A. Clarke and M.W. Poole, "Upgrading the Daresbury SRS with Additional Insertion Devices and its Implications for the Storage Ring Layout", 1996 European Particle Accelerator Conference, Sitges, Spain.

[3] V.P. Suller, et al, "Updated Plans for DIAMOND, a New X-Ray Light Source for the UK", PAC'95, Dallas, TX, pp 180-182.

[4] H. Kobayakawa, private communication.

[5] R. Klein, et al., "Beam Diagnostics at the BESSY I Electron Storage Ring with Compton Backscattered Laser Photons: Measurement of the Electron Energy and Related Quantities", Nuclear Instruments and Methods in Physics Research A 384 (1997) 293-298.

[6] M.E. Couprie, et al., "First Use of the UV SuperACO FEL : Fluorescence Decays and Conformational Dynamics of the NADH Coenzyme", Rev. Sci. Instrum., 65, 1485 (1994).

[7] P.M. Stefan et al., "Small Gap Undulator Experiment on the NSLS X-Ray Ring", PAC'95, pp 2435-2437.

[8] P.M. Stefan et al., "Insertion Device Development in the X13 Straight of the NSLS X-Ray Ring", these proceedings.

[9] R. Keller, et al., "Orbit Stability of the ALS Storage Ring", these proceedings.

[10] J-M. Filhol, et al., "Status Report on the ESRF", these proceedings.