SUMMARY OF THE 3RD INTERNATIONAL WORKSHOP ON BEAM ORBIT STABILIZATION – IWBS2004

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In 2004 the Paul Scherrer Institute was privileged to continue a series of two very successful **IWBS** *workshops, previously hosted by the SPring-8 Accelerator Division in 2001 [1] and 2002 [2].* **IWBS2004** *[3] was held at the Hotel Kirchbühl in Grindelwald, Switzerland during December 6-10, where 47 accelerator physicists from 12 countries gathered to talk about orbit stability matters. Excellent orbit stability is one of the key issues in 3rd generation light sources since the orbit has to be stabilized typically to 1/10th of the beam size at the location of the insertion devices, translating to sub-micron stability requirements over time periods ranging from ms to days. The upcoming linear accelerator based 4th generation light sources also have tight tolerances on their residual trajectory jitter which induces the need for slow, fast and "very fast" multi-bunch feedforward/feedback systems. The aim of this workshop series is to give people involved in orbit stability issues an opportunity to share their experiences, identify problems and discuss solutions.*

WORKSHOP PROGRAM

The **IWBS2004** program covered a number of different topics which were grouped into the following sessions:

- **FACILITY REPORTS:** The facility reports on orbit stabilization highlight the achievements/plans at present and future light sources.
- **NOISE SOURCE SUPPRESSION:** Proper specifications/modifications for/of various accelerator components allow the initial orbit motion without feedback to be minimized.
- **ORBIT MEASUREMENT/CORRECTION:** The remaining orbit motion must be measured and corrected; in particular the movement of insertion devices can induce significant orbit noise which needs to be compensated by means of feedforward and/or feedback schemes. "Top-up" operation guarantees a constant heat load on all accelerator and beam-line components and thus allows for high mechanical stability. Together with the utilization of fast orbit feedback systems, "top-up" operation makes it possible to achieve sub-micron stability on a scale from ms to days.
- **USER EXPERIENCE:** Two beam-line scientists from the SLS kindly agreed to share their experience with the workshop participants. They offered insight into the orbit stability requirements for experiments at their beam-lines.
- **STABILITY REQUIREMENTS IN 4TH GENERATION LIGHT SOURCES:** Position and energy stability requirements in linear accelerator (linac) based 4th generation light sources are demanding and require the use of slow and fast feedforward/feedback systems.

It was the organizer's deliberate intention to allow adequate time for discussions throughout the workshop. Coupled with the 38 excellent oral presentations of ≈20 min length (≈80 % of the participants gave talks) this inevitably led to a very tight schedule, which additionally included excursions to the SLS and the Jungfraujoch as part of the social program.

FACILITY REPORTS

The session "Facility Reports" made up a large fraction of the workshop program. Reports on orbit stability at 10 operating and 4 future ring based light sources were given. The session concluded with a presentation on orbit stabilization plans for the Large Hadron Collider (LHC) presently under construction at CERN.

The SPring-8 report focussed on the influence of the "top-up" operation mode on orbit stability which was introduced in May 2004. X-Ray beam stability at the experimental stations clearly improved and systematic current dependences of the orbit motion were reduced. Problems in the precise measurement of electron and photon beam positions remain. They are induced by systematic electron beam position monitors (BPMs) and X-Ray BPM (X-BPM) effects. BPMs in the vicinity of the Insertion Devices (IDs) exhibit ID gap, total current and filling pattern dependences and X-BPMs show a significant ID gap and phase dependence presently preventing SPring-8 from performing a "hard correction" on their readings. Local correction tests are planned in 2005 after improvement of the BPM hardware at the IDs. With "top-up" operation day/night related orbit variations can now be clearly resolved. The RMS fast orbit stability in the range 0.1-100 Hz at the IDs with $\sigma_{x/y}$ = 360/5 μm is presently x_{rms}/y_{rms} = 1/4 μm. The RMS slow orbit stability $<$0.1 Hz has been found to be of the order of 1-3 μm/week. The central energy is kept constant within $2{\cdot}10^{-5}$ full width. Although SPring-8 is "only" running a sub-Hz Slow Orbit Feedback (SOFB), it is able to near the sub-micron regime through careful noise suppression, indicating a Fast Orbit Feedback (FOFB) is unnecessary.

The PF ring at KEK features a global FOFB with 12 ms cycle time which will be redesigned in the course of an upgrade from 7 to 13 straight sections in the PF ring in 2005. A local FOFB (50 Hz to be upgraded to 1 kHz) in combination with a feedforward (FF) has been successfully tested to suppress distortions induced by a new undulator for the PF-AR ring which provides circular-polarized light by mechanical switching at 0.8 Hz. In the PF-AR ring a new injection scheme facilitating a single pulsed quadrupole has been successfully tested reducing orbit transients to ≈100/10 μm in the horizontal/vertical plane. It is foreseen to employ such a device for “top-up” injection into the PF ring and to reduce the residual oscillations further.

The Taiwan Light Source at NSRRC was upgraded in 2004 to suppress coupled-bunch instabilities by means of RF gap voltage modulation, super-conducting (SC) RF and a coupled-bunch feedback system. Orbit stability will be improved by “top-up” operation (already tested), mechanical/electrical source suppression, temperature stabilization and a global FOFB featuring a closed loop bandwidth (feedback BW) of $>$100 Hz. “Top-up” operation is scheduled for the end of 2005.

The Brazilian Synchrotron Light Source suffered from a longitudinal dipole oscillation which appeared as a horizontal orbit distortion proportional to the second order dispersion which could be cured by applying a phase modulation to the RF voltage. BPMs which were affected by an increased electromagnetic noise floor in the hall received additional shielding boxes.

BESSY is facing several new challenges. The femtosecond slicing bump needs to be reproducible to within 0.5 % (10 μm) of the total amplitude which is difficult to achieve with the present correction hardware. The mechanical/magnetic hysteresis of a SC wave length shifter (WLS) leads to 0.1 mm orbit excursions in the frequency range 0.5-10 Hz. Operation with low alpha optics settings is delicate since the horizontal orbit response to energy changes is amplified by a factor 10-200 making the use of the RF frequency as a corrector difficult. A local FOFB has been implemented for an APPLE II type ID regulating on two adjacent X-BPMs utilizing dedicated broad-band correctors. At 1.6 Hz a ≈30 dB photon beam jitter suppression could be achieved. But there is a clear need for a global FOFB. A feedback on the horizontal Split Mirror Unit (SMU) of a beam-line operating at an APPLE II double undulator has been established in order to improve the two-beam overlap. With feedback (2 Hz feedback BW) an angular stability of $<$0.1 μrad has been measured.

In 2004, ELETTRA underwent a complete machine realignment including the IDs to $<$100 μm RMS. Since realignment, tune and chromaticity changes cause very little orbit distortions, the RMS corrector strength is largely reduced, orbit corrections are converging faster and a quicker calibration of the ID corrector coils can be performed. A FF system for the Electromagnetic Elliptical Wiggler (EEW) allows to change the radiation polarization in AC mode up to 100 Hz without measurable orbit perturbation. Two local FOFBs with digital feedback electronics (sampling rate 8 kHz) are in routine user operation. They each involve two low-gap BPMs (14 mm) mechanically monitored to $<$50 nm with respect to a Carbon fiber column and four dedicated correctors. The PID controller is enhanced by a low pass filter with a cut-off frequency of 150 Hz to avoid power supply nonlinearities and harmonic suppressors at 50 Hz plus harmonics increasing the FOFB gain at these particular frequencies considerably. Sub-micron position ($<$0.2/0.9 μm) and angular ($<$0.02/0.2 μrad) stability has been achieved from 0-10/10-250 Hz. There are plans for a global FOFB involving all BPMs since crosstalk between many local FOFBs could become an issue. A full energy booster is under construction allowing for “top-up” operation.

The APS is a mature facility with very sophisticated orbit control capability. A canted ID geometry (0.5/-1/0.5 mrad) in 3 sectors of the APS allows to suppress the dipole radiation background, which otherwise would significantly contribute to the systematic errors of the adjacent X-BPMs. By integrating pairs of vertically sensitive dipole X-BPMs into the global FOFB (in operation since 1997) excellent long-term pointing stability of $<$1 μm (20 m from the source point) and $<$0.2 μrad has been achieved. Dipole X-BPMs are perfectly suited for integration into a FOFB since the photon beam profile does not change. A new “hard X-Ray” BPM is being designed to achieve 100 nrad long-term pointing stability which would make local steering for the beam-lines obsolete.

At the SLS “top-up” operation has proven to be an important prerequisite for high orbit and energy stability. The global FOFB running in user operation since ≈1 year ensures a complete decoupling of the ID operation up to 100 Hz. Slow ($<$1 Hz) X-BPM feedbacks running as an integral part of the FOFB following a cascaded feedback scheme guarantee sub-micron stability of the photon beam positions ≈10 m from the source point of presently 2 IDs. Several incidents related to the malfunctioning of the SLS cooling system have demonstrated how difficult it is to maintain the same high level of stability over long periods (weeks-months) if the operating conditions of the accelerator and the beam-lines cannot be kept constant.

In Spring 2004 a global FOFB employing digitized Bergoz [4] BPM signals (sampling rate 1.1 kHz, 60 Hz feedback BW) was introduced to user operation at the ALS. A SOFB (sampling rate 1 Hz) running at the same time reports proposed corrections to the FOFB which inhibits possible crosstalk between both feedbacks. X-BPMs are only used by feedbacks on the beam-line optics (1 h^{-1} to ≈ 10 kHz at infrared beam-lines). ALS is planning to upgrade to a full energy injector in order to be able to run in “top-up” mode at 500 mA with a granularity of 0.3 %, injecting single bunches every 30 s at a rate of 1 Hz. Gating signals will be provided to the beam-lines. First “top-up” tests revealed the necessity for improving the ring septum (leakage fields). Elliptically polarized undulators (EPUs) cause large beam size variations due to gap and phase dependent skew quadrupole fields of the IDs. Skew quadrupole FFs involving dedicated skew quadrupole correctors are being implemented. For ALS beam size stability is often more important than orbit stability.

Until the end of 2004 ESRF operated a global SOFB ($\leq$0.1 Hz feedback BW) with 224/96 BPMs/correctors, a global vertical FOFB (0.1-150 Hz feedback BW, correction deadband to decouple SOFB from FOFB) based on 16 BPMs/correctors (air coils) and 4 horizontal local FOFBs at the most sensitive IDs. Eventually the observed crosstalk between local FOFBs, due to non-closure of the 4-corrector bumps at high frequencies, motivated the upgrade to a global FOFB with 200 Hz feedback BW for both planes involving 32/24 BPMs/correctors. The new FOFB is operational and outperforms the old local FOFB arrangement.

In spring 2006 SOLEIL will commence user operation with 10 initial beam-lines. Sub-micron orbit stability will be required at the IDs on the scale of a few ms to hours which makes a FOFB and "top-up" operation indispensable. The lowest eigenmode (measured) of the girders/dipoles has been shifted from 44/12.7 Hz to 46/27 Hz thanks to a more rigid fixation of the dipoles on the girders. The global FOFB will be based on digital BPM electronics from "Instrumentation Technologies" [5]. It is planned to have a global SOFB (0.01 Hz feedback BW) involving 120 BPMs and 56 slow correctors per plane ready for commissioning and a global FOFB (0.01-100 Hz, 8 kHz sampling rate) utilizing 120 BPMs and 46 fast correctors (air coils) in each plane a few months later. SOFB and FOFB will run simultaneously and will be integrated using a master/slave scheme as is the case at APS and ALS. The straight section BPMs are decoupled from the vacuum system by means of bellows and mounted on independent steel (later thermally stabilized or from Invar) supports.

DIAMOND will be open to users in 2007. Similar stability requirements as in the SOLEIL case have led to comparable solutions. The very flexible girder design allows for movement in 5 degrees of freedom but as a result the structure exhibits the first eigenmode at "only" 29 Hz. The positions of the girders will be measured using a horizontal (HPS) and vertical (VPS) linear encoder (self-calibrating) based positioning system. They are intending to have one global FOFB using 168 BPMs and 168/96 slow/fast correctors in each plane where 4 of the fast ones will be located in each straight in order to allow for arc decoupled ID beam steering.

The site of ALBA/CELLS has been selected. The proposed site, although not ideal, is not as bad as preliminary measurements first indicated. As it is often the case the criteria used to select the site were not of a technical nature.

In mid-2007, DESY will start to transform the present HERA injector PETRA II (circumference 2304 m) into a synchrotron light source. One octant of the machine will be rebuilt to serve 13 undulator beam-lines (E = 6 GeV, ϵ_x = 1 nmrad, I = 100 mA). User operation is scheduled for 2009. The low emittance, ϵ_x, is achieved by introducing 2 damping wiggler sections of 2$\times$40 m length. This imposes tight constraints on the allowed spurious dispersion in these sections ($\eta_{x/y}$ = $<$20/5 mm, similar values for ID locations) thus requiring dispersion correction to be an integral part of the planned SOFB (feedback BW $<\approx$0.1 Hz). Sub-micron stability requirements for the ID octant enforce the necessity for a "local" octant FOFB (feedback BW $\approx$0.1-100 Hz). The FOFB extends into the adjacent "old" octants in order to be able to maintain the small vertical emittance (1 % coupling assumed).

The Large Hadron Collider (LHC) (27 km circumference) at CERN is scheduled to be ready for start-up in 2007. Since it uses SC magnets with a somewhat "extreme" design in order to provide a dipole field of 8.3 T at 7 TeV, a fast beam loss of $<10^{-7}$ of each of the beams with 350 MJ stored energy at 7 TeV may quench a magnet (recovery time $\approx$6 h). Due to very limited apertures in the interaction regions the primary collimators must be closed to 5-7 σ (σ = 300 μm in the arcs) of the beam which leads to tight (for the proton world) constraints on the orbit stability at collimators and absorbers of $<\approx$50-70 μm. 528 BPMs/ring retrieve orbit data at a sampling rate of 50 Hz with a resolution of $<$1 μm. 280 slow (BW 1 Hz) SC correctors/plane/ring are employed for orbit correction. The planned SOFB which will have a centralized structure must meet high reliability requirements in order to minimize the risk of a magnet quench.

NOISE SOURCE SUPPRESSION [1]

Well before feedback systems, the identification and minimization or possible removal of noise sources were essential to the achievement of state-of-the-art orbit stability. The session covered different issues that nethertheless form a representative sample of cases.

The residual orbit distortion associated with the operation of the IDs is one of the major instability sources for all of the synchrotron facilities. FF systems based on correction coils are generally implemented and can provide good performance for IDs with slowly varying gap/phase. In the case of devices with a relatively fast switching of the radiation polarization, specific noise suppression strategies are needed to take into account dynamic effects. In particular, the orbit distortion due to the operation of these devices must be clearly measured and disentangled from the background noise present in the beam, so that appropriate values of the correction coils look-up tables can be obtained. A case was presented for an APPLE II type undulator installed at SPring-8, with the radiation helicity varying at 0.1 Hz following a trapezoidal driving pattern. A novel method was shown that separates the effect of static and dynamic field errors. Given the linear behavior of the system, correction values that correspond to different driving patterns are obtained only by scaling the correction data associated to the dynamic field errors.

With the general trend of synchrotron light sources towards "top-up" operation, perturbations produced on the stored beam by the injection shots are to be con-

[1] This section has been contributed by D. Bulfone, ELETTRA.

sidered as an additional source of noise. In addition to the gating signals provided to the experimentalists to temporarily disable data acquisition, efforts are going on to make user transparent injections. A significant example was reported by SPring-8, where a combination of passive and active noise suppression techniques is adopted. The first include careful equalization of the kicker pulses, kicker re-alignment to avoid crosstalk in the vertical plane and adjustment of the strength ratio of the sextupoles inside the injection bump to minimize non-linear effects. The latter consists of FF systems on both planes based on pulsed corrector magnets. The transverse multi-bunch feedback also helps by shortening the duration of the perturbation. With such countermeasures in operation, SPring-8 users do not suspend data acquisition during injection.

The cooling water flow can induce mechanical vibrations of the storage equipment (magnets, vacuum chamber etc.), which affect the beam stability through different mechanisms. At SPring-8 the magnetic field created by eddy-currents in a vacuum chamber vibrating inside quadrupoles produces orbit perturbations up to 200 Hz. The installation of additional supports has already improved the situation. Further progress is being made, however, by measurements and modal analysis of the chamber sections vibrations, which can be damped by specifically designed supports.

The session closed with a report on the experience gained with the dynamic alignment system of the SLS, where magnets are rigidly mounted on girders which are equipped with a complete set of girder/BPM position sensors and girder movers. Girder re-alignment using the movers proved to be convenient. The different position sensors provide data that can be usefully correlated to temperature changes and long-term settlements. The potential for orbit correction by means of "on-line" girder adjustments has also been demonstrated, but the interactive use of the system still looks cumbersome due to its complexity, the intrinsic long response times and the non-negligible risk of the involved operations.

ORBIT MEASUREMENT/CORRECTION

The first part of the "Orbit Measurement/Correction" session was dedicated to technological advances in diagnostics and feedback hardware. It was opened by a stimulating rapporteur talk on the "SLS Workshop on Beam Stability", held at PSI on Sep 6, 2004. The intention of the internal meeting was to review the performance and limitations of the actual stability, relevant hardware installations and the applied correction schemes at the SLS from the perspective of present and future user and operational requirements [6].

The digital electron beam position processor "Libera" from "Instrumentation Technologies", a commercial descendant of the digital BPM system developed for the SLS, allows simultaneous position readouts with MHz, kHz and Hz BWs providing sub-micron resolution (BPM geometry dependent) at sampling rates of a few kHz. Applying multiplexing techniques on the 4-channel system allows to reduce systematic effects (self-calibrating system, e.g., beam current dependence). Connectivity options like fiber link ports and extra processing power make the processor suitable for building FOFBs. SOLEIL and DIAMOND have made "Libera" their digital BPM system of choice.

At DIAMOND all 204 BPMs in the accelerator chain use "Libera" electronics. In the storage ring the primary BPMs at the start/end of the straight sections have increased sensitivity through smaller aperture. They are decoupled through bellows and monitored with respect to a reference pillar as in the SOLEIL case. Their RMS noise with 1 kHz BW in the current range 60-300 mA has been measured to be $\approx$0.3 μm. The SOFB (10 Hz sampling rate, 0.5 Hz feedback BW) will use EPICS with the IOCs running inside "Libera". A TRACY-2 based "virtual accelerator" implemented on a Soft-IOC allows to test applications before commissioning. The FOFB (aimed at feedback BW $>$100 Hz) running at sampling rates of up to 10 kHz will employ dedicated feedback CPU boards to run the correction algorithm (different to SOLEIL case where exclusively "Libera" is used).

At PSI a generic VME PMC carrier (VPC) board is currently under development and is likely to become the common digital platform for diagnostics and feedbacks at PSI (e.g., new proton BPMs, FOFB integration of X-BPMs, PROSCAN, LEG, Femto, DESY-RF collaboration) [7]. The analog/digital front-ends will be customized depending on the analog diagnostics hardware, whereas the digital back-end hardware will be identical with some common firmware/software. The VPC board is also a possible candidate for the replacement of the present SLS FOFB hardware and the digital BPM system. A future SLS BPM system might have single bunch resolution, allowing for beam-based calibration of BPM bunch charge dependence, as well as for a "fusion" of BPM and bunch charge monitor hardware for FOFB, multi-bunch feedback and bunch-pattern feedback.

The not yet commissioned FOFB at SPEAR-3 utilizes an Echotek digital receiver as part of the 4-channel BPM system consisting of 24 BPMs (54 Bergoz BPMs for SOFB). BPM samples are streamed over dedicated point-to-point Ethernet links (no TCP/IP) to a central FOFB controller at a rate of 4 kHz. The corrections are fed into power supply controllers with 24-Bit DACs. The copper chamber induces a correction cut-off frequency at $\approx$120 Hz.

The SOFB for the LHC foresees only one central SOFB processing unit utilizing the SVD algorithm and a PID controller extended by a "Smith Predictor" which compensates for constant propagation delays induced by e.g., computation time, task switching or network transfers. More than 1000 BPMs and correctors distributed over 27 km of circumference make it a delicate task to handle, in particular network delays on the switched GBit Ethernet (not dedicated to SOFB) and hardware failures. Special routers with prioritization (“Quality of Service”, QoS) on the hardware level guarantee a response time of ≈320 μs to all involved nodes.

“Bergoz Instrumentation” is promoting VIAQS, a data acquisition and control server package to simplify the operation of accelerator diagnostic devices. It’s aim is to ease the task of implementing an EPICS based SOFB using Bergoz BPMs.

In the second part of the session the latest advances in the refinement of orbit correction schemes were presented. Since DELTA is suffering from large alignment/magnetic errors of machine constituents and improper placements of BPMs/correctors, global orbit corrections can easily saturate correctors. Therefore, their SVD based correction scheme has been extended to include constraints imposed by the maximum available corrector strength.

The proposed Super-SOR light source, to be built near Tokyo, includes a global FOFB in its design (sampling rate $>$2 kHz, feedback BW $>$100 Hz) aiming for sub-micron stability at the location of the IDs. An eigenvector method with constraints (EVC) has been developed which allows an “hard” correction on crucial BPMs or X-BPMs adjacent to IDs to be performed. This is achieved by introducing position references as constraints to the algorithm while simultanously relaxing conditions elsewhere, all within one global correction scheme. The algorithm has been successfully applied to the PF(PF-AR) ring at KEK where 4(6) out of 65(83) BPMs were constrained to zero.

The PLS in Korea operates a SOFB at a correction rate of ≈0.2 Hz. In 2004 the machine was equipped with new corrector power supplies (controllers of BESSY type) with 20-Bit resolution. The implementation of a global FOFB is under consideration. Since PLS is in decaying beam operation, a large fraction (≈80 %) of the observed changes in the BPM readings is caused directly or indirectly by variations in the beam current (180-120 mA in ≈7 h). Main contributions are the BPM electronics dependence on beam current and vacuum chamber movements due to the change of the synchrotron radiation heat load. A dependence of the BPM electronics on ambient temperature has also been observed. In order to compensate for the BPM electronics dependence on beam current, look-up tables have been successfully implemented. It turned out to be difficult to compensate for the chamber movement. “Top-up” operation, however, would ultimately solve the problem.

At the SLS a global FOFB with a sampling rate of 4 kHz is in operation since one year providing submicron stability at the IDs in the range 0.1-100 Hz [8]. The FOFB has a decentralized structure consisting of 12 intercommunicating BPM sectors (digital BPM system with FOFB capability developed at PSI) exchanging BPM readings through dedicated unidirectional fiber optical links. Each sector performs the necessary sub-matrix multiplications for the SVD based orbit correction on a dedicated DSP and applies the proposed corrections to the correctors within the sector. The orbit stability on the time scale ≈6 ms - 1 s is mainly limited by the BPM/corrector resolution, the FOFB system latency and the induced eddy currents in the vacuum chamber, whereas limits on longer time scales are mainly imposed by the reliability of hardware components, systematic errors of the BPMs and the thermal stability of the machine (“top-up” operation). A filling pattern dependence of the BPM readings was observed which became manifest in a significant change (≈2 μm peak-to-peak) of the reference orbit while X-BPM readings at 2 IDs were kept constant through a change of the reference settings of the two adjacent BPMs (X-BPM feedback). Meanwhile a filling pattern feedback has been implemented [9] which eliminates these systematic variations. A 30-40 ms long transient orbit change of 300 μm at dispersive BPMs is observed whenever the RF frequency is altered. A use of the frequency modulation input of the RF generator instead of the IEEE interface would most probably resolve the problem. Soon the FOFB will be upgraded/extended for the integration of additional BPMs (Femto) and X-BPMs.

At ANKA the beam energy was calibrated by means of resonant spin depolarization, as previously done at other ring based light sources (e.g., BESSY, ALS, PLS, SLS [10]). One of the main aims of the presentation was to encourage the community to make use of this precise calibration technique (ΔE/E≈10^{-5}) since all prerequisites are already fulfilled in most low and medium energy light sources:

1. the existence of a finite transverse electron polarization of a few 10 %,
2. a Touschek dominated beam which leads to a significant decrease in lifetime (typically $>\approx$10 %) whenever the polarization level is dropping to zero since the Touschek scattering process is polarization dependent,
3. a vertical kicker being capable of exciting and thus depolarizing the beam at the spin precession frequency ν which is directly related to the energy factor γ ($\nu = a\gamma$, a=anomalous part of the g-factor).

By depolarizing and measuring γ at different RF frequencies the linear and even the quadratic momentum compaction term can be determined.

USER EXPERIENCE

In this session, two SLS beam-line scientists reported on the orbit stability requirements of experiments carried out at their beam-lines and compared them with the present performance of the SLS. The opening talk covered the surfaces/interfaces microscopy (SIM) beam-line operating an APPLE II double undulator (2×UE56). The measurement of absorption spectra requires a frequent movement of ID gaps/phases, which should not effect other beam-lines. Since it is a difficult task to make these IDs transparent on a

μm level through shimming and FFs for all thinkable modes of operation, the remaining orbit distortions are left to the FOFB to handle. On critical time scales (10 Hz - 1/3 h^{-1}) a horizontal/vertical orbit movement of 0.5/1 μm, leading to an intensity/energy variation of $\approx$0.1 % (no normalization) /$\approx$1 meV, can be tolerated for the measurement of circular polarization difference absorption spectra. With the SLS FOFB running the aforementioned requirements are fulfilled. The SOFB is clearly not sufficient.

The protein crystallography beam-line (PXI) operating an in-vacuum undulator (U24, replaced by U19 in 2004) has always been imposing high stability requirements on the SLS since the beginning of user operation in 2001. Knowing the magnetic properties of U24 very well the PXI beam-line could deduce the electron beam energy and spread from the undulator spectrum. Since the field strength in a small-gap undulator strongly depends on the absolute vertical beam position within the ID, the vertical orbit should be confined to $< \pm$10/100 μm over a user-/SLS-run ($\approx$1 day/several weeks). In multiple wavelength anomalous dispersion (MAD) experiments, photon beam energy stability requirements (ΔE/E$<10^{-5}$) translate directly into angular orbit stability Δy'$< \pm$1.5 μrad (Se K-edge at 12.66 keV, Si (111) mono). These requirements are fulfilled by the SLS running with SOFB provided the settings of other IDs are kept constant. The FOFB makes ID operation transparent but there are indications that the noise on the photon intensity (0.5-500 Hz) increases which needs further investigation. Future time resolved experiments may require orbit stabilization to frequencies $>$100 Hz.

STABILITY REQUIREMENTS IN 4TH GENERATION LIGHT SOURCES

The closing talk of the "Orbit Measurement/Correction" session, on beam stability improvements in the SPring-8 linac necessitated by "top-up" operation stability requirements in terms of bunch energy, intensity and purity already highlighted some of the challenges of 4th generation light sources. In 2004, the linac achieved an RMS energy/current stability of 0.01/1.9 %, starting from $>$1/20 % in 1998, mainly by means of careful source suppression (ambient/klystron temperature, RF amplitude/phase, synchronization with ring RF), implementation of an energy compression scheme (ECS) and feedback based stabilization of the beam position to $\approx$60 μm.

It was followed by a report on beam stability issues covered at the Free Electron Laser (FEL) Conference **FEL2004** [11]. The talk was meant to introduce the auditorium to the specific stability problems of FELs. Different FEL types (storage-ring FELS, high average-power devices, single-pass devices) were discussed highlighting the critical issues followed by a comparison of the stability requirements. Storage-ring FELs impose serious constraints on the longitudinal (RF frequency/multi-bunch modes) and transverse stability (μm level) of the circulating beam. The average output power is only $<$1 % of the intra-cavity power. In general, resonator based FELs need high average current whereas single-pass FELs need high peak current. It can be distinguished between "start-up from noise" (SASE) and "controlled startup" (SEED) single-pass FELs. SASE FELs (e.g., LCLS, TTF, XFEL) provide high output power, are flexible in wavelength tuning but suffer from a "spiky" photon beam spectrum. In return SEED FELs (e.g., BESSY, FERMI, TTF) feature an improved spectral purity (e.g., HGHG: $\approx$0.23 nm FHWM) and intensity stability.

Compared to a storage ring which is like a "spinning top" (intrinsically stable: steady state, closed orbit, radiation damping, beam clearing through dynamic aperture limitation, small kHz noise BW, ΔE/E$<10^{-5}$ in "top-up" mode) a linac is like an "archery" (potentially noisy: pulsed, open trajectory, no damping, no beam clearing, large GHz noise BW, ΔE/E$>10^{-2}$). Among the sources of noise in single-pass devices are AC line fluctuations, switch-tune pulse-to-pulse jitter, switching noise fluctuations, AD/DA digitizing noise, temperature fluctuations and ground motion. Feedbacks are mostly not possible necessitating the use of feedforwards between micro-/macro-pulses instead. The required transverse orbit stability when applying the "10 % of a σ" stability rule is typically of the order of a few μm (fs-as for the longitudinal motion). Within the undulator the orbit must be controlled over a few gain-lengths in order to ensure the overlap between optical field and the electron beam, which is a prerequisite for reaching saturation.

The SASE FEL to be built at DESY (XFEL), featuring an 1400 m long 20 GeV SC linac, requires low emittance (ϵ_N=1 μmrad), low energy spread (ΔE/E $<$0.02), extremely high charge density (the XFEL will accelerate 3200 bunches of 1 nC charge and 80 fs length per pulse at a rate of 10 Hz) and a long undulator (L=700 m). The "bullet" like beam, with 20-30 μm beam size, requires sub-micron (or fs) stability in all three dimensions following the "10 % of a σ" rule. Experiments at the end of the 800 m long beam-lines demand a position stability of 0.1σ in the last part of the undulator and a pointing stability of $\approx$1 μrad.

The XFEL will have the need for feedforwards between micro-/macro-pulses. Up to now the single bunch BPM resolution is only $<$50 μm for cold button and cavity BPMS which is not sufficient to fulfill the stability requirements. A prototype of a vertical "feedback" system for the VUV-FEL at DESY employing the same linac structures as the XFEL has been installed in the TESLA test facility (TTF). It has been demonstrated that the digitally controlled system, which utilizes 2 BPMs/kickers, is capable of confining 180 bunches within $\pm$50 μm, compared to 400 μm peak-to-peak without "feedback".

CONCLUSION

IWBS2004 was a very exciting and fruitful workshop. Most of the represented operating or future ring based light sources are using or proposing very similar techniques to achieve high orbit stability as there is firstly careful source suppression by means of:

- hall/tunnel/cooling-water temperature stabilization including simulations of tunnel temperature distributions,
- careful FEM based structural analysis of girders (ensuring an excellent element-to-element alignment) and whole assemblies including magnets and vacuum systems,
- a tight magnetic and mechanical error budget,
- low power supply noise (often digital control),
- utilization of beam-based alignment techniques in order to reduce on quadrupole-to-BPM misalignments,
- linear encoder based systems which allow the mechanical stability of girders, BPMs and other accelerator components to be judged and monitored,
- "top-up" operation to ensure a constant synchrotron radiation heat load, thus allowing a thermal equilibrium and therefore excellent stability to be achieved.

Secondly high resolution/BW BPM systems (often digital) allow an excellent orbit measurement on the sub-micron level over a range of a few kHz. Sophisticated FF schemes utilizing BPMs and X-BPMs can make ID operation nearly transparent while keeping the photon beam position constant at the X-BPMs of the ID. Together with global/local SOFBs and FOFBs based on high resolution BPMs/X-BPMs and correctors orbits can be stabilized to the sub-micron level on time scales ranging from ms to several days allowing also for a completely transparent operation of the installed IDs.

The stability requirements of linac based 4th generation light sources ("archery") are on the micron to sub-micron level, but are much more difficult to achieve than in ring based sources ("spinning top"). Noise source suppression (particularly RF related) becomes extremely important. High precision single-pass BPM diagnostics, which at present have not yet met the requirements, are necessary in order to implement high BW FF schemes between micro-/macro-pulses at the XFEL. It became apparent that these machines pose a real challenge to the accelerator community.

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Fig. 1: **IWBS2004** participants on December 8, 2004.

A strong wish has been expressed to have **IWBS2006** hosted by ALS at LBNL in close collaboration with LCLS at SLAC. Therefore **IWBS2006** naturally will put a stronger focus on linac based 4th generation light sources.

REFERENCES

[1] **IWBS2001**: *http://acc-web.spring8.or.jp/∼oper/beam-stabilize-ws/index-e.html*, SPring-8, Hyogo, Japan, Oct 15-16, 2001.

[2] **IWBS2002**: *http://www.spring8.or.jp/e/conference/iwbs2002/*, SPring-8, Hyogo, Japan, Dec 4-6, 2002.

[3] **IWBS2004**: *http://iwbs2004.web.psi.ch/*, Grindelwald, Switzerland, Dec 6-10, 2004.

[4] Bergoz Instrumentation, *http://www.bergoz.com/*.

[5] Instrumentation Technologies, *http://www.i-tech.si/*.

[6] V. Schlott, *SLS Workshop on Beam Stability*, PSI Scientific Report 2004, VI.

[7] B. Keil *et al.*, *Status and Perspectives of the Generic VME PMC Carrier Board (VPC)*, PSI Scientific Report 2004, VI.

[8] M. Böge *et al.*, *Beam Dynamics Activities at SLS*, PSI Scientific Report 2004, VI.

[9] B. Kalantari, V. Schlott, T. Korhonen, *Bunch Pattern Control in Top-up Mode at the SLS*, PSI Scientific Report 2004, VI.

[10] S.C. Leemann, M. Böge, *Precise Beam Energy Calibration at the SLS Storage Ring*, PSI Scientific Report 2002, VI.

[11] **FEL2004**: *http://www.elettra.trieste.it/fel2004/*, Trieste, Italy, Aug 29 - Sep 3, 2004.