PERFORMANCE AND TRENDS OF STORAGE RING LIGHT SOURCES

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Abstract

We present an overview of the performance of the latest generation of operating storage ring light sources. Emphasis is given to the comparison of design parameters to the achieved performances. Trends and innovations of established light sources to meet the increasing user's demand for high brilliance and different time structures will be presented. Report on upgrades and improvements will be given including orbit stability, top-up, feedback systems, lower-ID gap operation and a review of the activities for the generation of ultra-short radiation pulses in storage rings.

INTRODUCTION

Third generation light sources started operation in the early nineties, with the commissioning of the ESRF in 1992 being the first of a series of about twenty storage ring light sources currently running today. These facilities are generally foreseen to operate for twenty and more years and they have to undergo several improvements and upgrades if they want to match the continuously evolving users' requirements and the competition imposed by new state-of-the-art projects. Users' applications in fields as diverse as physics, biology, medicine, archaeology and many others, require a continuous improvement and extension of properties of synchrotron radiation such as

- Photon energy
- Photon brilliance
- Photon flux
- Coherence
- Stability
- Polarisation
- Time structure
- Larger capacity

The delivery and the improvement of such photon beam qualities imply a series of Accelerator Physics and Accelerator Technology challenges. The storage ring parameters to improve to fulfil these requirements can be summarised in

- Lower emittance
- Low energy spread
- High average current
- Smaller ID gaps
- Beam Stability (feedback systems, Top-Up, etc.)
- Short bunches or short radiation pulses
- Longer straight sections and canted IDs

The requirements for each machine are generally tailored to the scientific needs of the user's community that will exploit it, nevertheless many common trends have emerged in the evolution of the various storage ring synchrotron light sources.

STORAGE RING OPTICS

The average brilliance of third generation light sources is mostly determined by the electron beam emittance for non diffraction limited sources. Therefore the implementation of low-emittance lattices is a crucial aspect in improving the performance of a storage ring light source.

Low-emittance lattice designs are based on well known schemes such as Double Bend Achromat (DBA) or Triple Bend Achromat (TBA). These lattices are characterised by Theoretical Minimum Emittance (TME) values which define the lowest achievable emittance. Their practical implementation has achieved emittances which are usually a few times higher than the TME. The design of more recent light sources has reduced the emittance by breaking the achromatic condition allowing a non zero dispersion in the straight section. Despite the dispersive contribution, the effective emittance of these lattices is lower than the emittance of the corresponding achromatic version and they achieve a higher brilliance. Modern third generation light sources operate with a nominal emittance of few nm, (Diamond 2.7 nm, SOLEIL, 3.7, SSRF 3.9 nm)[1-3]. Established facilities have upgraded their initial design in the past to fully exploit the benefit of these schemes. ESRF reduced the emittance from 7 nm to 4 nm[4], APS from 7.5 nm to 2.5 nm[5] which represent the lowest natural emittance achieved to date in operating machines. Among the most recent facilities a noticeable effort towards reducing the emittance is pursued at Petra-III[6] and NSLS-II[7], where a sub-nm emittance is achieved by the use of damping wigglers. The NSLS-II design foresees also the use of weak dipoles (0.4 T) in order to enhance the effect of the damping wiggler on the emittance. A careful control of linear coupling has also allowed the increase of the brilliance providing diffraction limited sources at least in the vertical plane. Recent light sources can correct the emittance coupling well below 1% reducing the vertical emittance to few pm[8].

Linear Optics

The practical implementation of the nominal optics in the storage ring has been vastly eased and improved by lattice calibration algorithm such as LOCO[9] and its improvements[10]. All modern facilities report values of β-beating of 1% and below. The dispersion in bending is usually very well controlled and the nominal horizontal emittance is typically achieved with errors well below 10%. Many facilities report emittance coupling correction to 0.1%. The main issue in reducing emittance coupling is related to the poor Touschek lifetime, although recent studies at SLS and ALS have shown some benefits of low coupling operation related to lower loss in the vertical apertures due to a smaller beam size. The SLS reports a measured emittance coupling of $5 \cdot 10^{-4}$ corresponding to an emittance of 3.2 pm which is the lowest values achieved in operating storage ring light sources[8]. The effect of the insertion devices on the linear optics can be controlled with LOCO or with simple local correction schemes which provide feed-forward tables for the correction of the β-beating and tuneshifts induced by the IDs. The full exploitation of these correction algorithms requires the implementation of independently powered quadrupole magnets.

Nonlinear Optics

Low emittance lattices are associated with strong focussing quadrupoles and large natural chromaticities that must be corrected by strong chromatic sextupoles. The aberrations introduced by the sextupoles generate a complicated nonlinear beam dynamics that reduces the dynamic aperture available to the beam and can generate a poor injection efficiency and a poor lifetime. The optimisation of the nonlinear beam dynamics is a long process that lasts for the whole design stage of a storage ring. Usually the main target of this optimisation is the Touschek lifetime, which requires a large momentum aperture of the ring. Recent storage ring light source are designed to achieve up to several per cent momentum aperture (6% at SOLEIL, 4% at Diamond). The correct implementation of the nonlinear machine model is still the subject of extensive studies at various machines[11].

Several experimental techniques have been used for the control and the correction of the nonlinear beam dynamics. The Frequency Map Analysis (FMA)[12] is a tool that has been extensively used in the design phase of many storage ring light sources to optimise the global nonlinear dynamics. More recently, the FMA has also become an experimental tool for the investigation of the nonlinear behaviour of the machine and its comparison with the model. The first experimental measurement of the Frequency Map was performed at ALS[13], followed shortly by the ESRF[14] and more recently by Diamond[15] and SOLEIL[16].

The experimental investigation of the dynamic apertures is performed with pinger magnets which apply kicks directly probing the aperture available to the beam. Alternatively, the lifetime as a function of horizontal and vertical collimator aperture is monitored to probe the edge of the dynamic aperture available to the beam. Measurements of the lifetime as a function of RF voltage are used to probe the momentum aperture. Results at various storage ring light sources[11] indicate that the measured dynamic aperture and momentum aperture are generally smaller than the numerically computed values indicating that the modelisation of the nonlinear ring captures only partially the complexity of the underlying dynamics. The careful description of magnetic field errors obtained from measurements of magnets and IDs, including fringe fields and dipole edge effects, appears mandatory for a successful description of the nonlinear beam dynamics. The experimental characterisation of the nonlinear ring model is nevertheless short of a comprehensive and robust solution such as the one that LOCO-like algorithms provide for the linear optics and it is an active research field.

ORBIT STABILITY

The stability requirements on the electron beam are generally set to 10% of the beam size and angular divergence over a frequency range extending up to 100 Hz. These requirements may be defined more stringently at various machines (5% at APS [17]) and it is not uncommon that particular beamlines, e.g IR beamlines, require orbit stability of 1% of the beam size and angle divergence above 100 Hz. This entails sub-μm stability at the Electron Beam Position Monitors (EBPMs) often combined with the direct control of the photon beam with the Photon Beam Position Monitor (PBPMs). The stability has to be guaranteed on an increasing range of frequencies which cover slow disturbances (> 1 day), medium disturbances (0.1 Hz to 1 day) and fast disturbances (0.1 Hz up to 100 Hz or more).

Short term stability

The short term stability is mainly affected by ground vibrations, effects related to ID gap movements which are not fully compensated by feed-forward tables and power supply ripples. Ground vibration measurement campaigns are performed to characterise the ground motion spectra and to identify the causes of the main sources of vibrations and damp them wherever it is possible. Pairing of magnets on girder structures can reduce significantly the impact of these vibrations on the stored electron beam and a careful analysis of the girder resonances is performed in order to push the resonant frequencies to few tens of Hz where the ground vibration power spectral density (PSD) is naturally low [18-19]. Complementary cures involve the introduction of visco-elastic damping link on the girder structure [20]. Recently built light source have taken this aspects into account from the initial design of the storage ring, using piled concrete slabs and carefully optimised girder structures. At Diamond the integrated beam motion PSD over a range 1-100 Hz is 2.5 μm in horizontal and 0.4 μm in vertical at the ID source point, which is within the 10% stability requirements [18].

The ultimate remedy against high frequency vibrations (1-100 Hz) is the implementation of a fast orbit feedback (FOFB). ALS, APS, Diamond, ESRF, SLS and SPEAR3 have operating FOFB systems most of which achieved sub-μm stability up to 100 Hz. Other recently built light source have a FOFB programme [21]. The extension to higher frequencies appears challenging and requires careful optimisation of the FOFB components.

To increase the control on the stability of the photon beam several light source [22] have included PBPMs in their feedback system.

Medium and Long term

Orbit stability on a medium time period (0.1 Hz to 1 day) is mainly affected by thermal effects related to the varying thermal load with decaying beam current or with temperature variation of the tunnel, instrumentation areas and experimental hall and with day/night temperature variations. A careful control of the tunnel temperature to 0.1 C and of the experimental hall to 1 C is now routinely required at various light sources. Top-Up operation is a measure that guarantees a constant thermal load on the vacuum components and is part of the upgrade programme of many facilities.

Long term stability issues arise from to ground settlements or weekly gravitational effects and are generally counteracted by long term realignment of the machine elements.

TOP-UP

Top-Up operation consists in the continuous refill of the current lost due to lifetime losses. A storage ring operating in Top-Up mode typically refills the current at fixed time intervals in order to keep the stored current stable within 0.1-1%. Top-Up operation in synchrotron light sources was pioneered at the APS in 2001 and then used at the ESRF, SLS, Spring8 and TLS. Recently commissioned light sources will implement Top-Up shortly [23] while older light sources have vigorous programmes to retro-fit Top-Up operation [24].

Top-Up operation has many advantages. Firstly, it allows the user to benefit from a constant stored current, i.e. a constant photon flux, with a higher average value, over longer time periods. Secondly, it provides a constant thermal load on the vacuum chamber and beamline component, reducing thermal drifts thereby improving the medium term stability of the storage ring operation. Finally, Top-Up operation reduces the adverse effects of a limited stored beam lifetime. New machine operating modes, normally prohibited by too short a lifetime, can be explored and offered to the users. Spring-8 reported an increase of the average brilliance by a factor three thanks to a lower emittance lattice that could be operated with Top-Up[25]. Predicted benefit of Top-Up operation at ALS will make it compete with state-of-the-art storage ring light source such as Diamond and SOLEIL[26].

The disadvantages of Top-Up are related mainly to safety issues due to the fact that the injection in the storage ring occurs with the shutters open. Radiation hazards and the injection efficiency with IDs closed have to be carefully monitored and optimised. All facilities currently operating Top-Up, report injection efficiencies above 75%.

Radiation dose calculations and measurements with shutters open and IDs closed are performed to assess the impact of accidental channelling of the injected beam down a beamline. Complicated Accelerator Physics studies are performed to identify which faulty scenarios can generate a Top-Up accident. A system of interlocks is usually defined as a result of the Top-Up safety simulations. The specific interlocks requirements depend on the facility. Typically a stored beam interlock and the control of the magnet setpoint of a few particular magnetic elements are adequate[27].

Another disadvantage of the continuous injection is the generation of orbit transient in the stored beam due to the non perfect closure of the injection bump. These residual oscillations have to be carefully minimised and very stringent requirements are imposed on the uniformity of the injection kicker pulses. Typically, residual oscillations of few hundreds μm peak-to-peak at average β BPMs are reported. The situation is slightly complicated at some light sources such as APS, SPRING8, SPEAR3 where the injection bump extends over more than one cell and goes through one or more sextupole magnets. The corresponding amplitude depend effects have to be carefully taken into account. Finally some machines (e.g. APS) deliberately inject with a non-closed bump to maximise the injection efficiency, in these cases the injection transient is intrinsically unavoidable.

The effect of the orbit transient is generally perceived by the users as a blow up of the beam with a corresponding reduction in the intensity of the photon beam. Beam blow up is contained within 30% of the beam size and last for a period of few transverse damping times. Some facilities use the transverse multibunch feedback system to further reduce the period where the stored beam orbit is perturbed. The timing system delivers gating signals which allow the beamline to stop the data acquisition while the beam is injected and the orbit is perturbed. It is clear however the minimisation of the orbit transient remains an important issue to achieve a successful Top-Up operation.

An obvious prerequisite of a Top-Up operation is a full energy injector: modern light source have a full energy booster while older machine such as ALS and ELETTRA have upgraded to a full energy booster injector.

HIGH CURRENT

In order to increase the photon flux delivered to the users, newly operated light sources are aiming at high current operation up to 500 mA (e.g. SOLEIL, SPEAR3). Several operating light sources have significantly exceeded their current design target by large factors: ESRF currently operates at 200 mA instead of 100 mA, Bessy-II operates well above 100 mA.

High current operation requires a careful design of the vacuum chamber components to ensure they can withstand the thermal load generated by the photon beam and their contribution to the machine impedance is minimised to reduce the adverse effect of collective effects. A careful analysis of the impedance of the various components of the ring is performed with the aim of building impedance databases based on extensive numerical simulation with codes such as MAFIA and GdFidl [28].

Collective effects limit the high current operation. Multibunch effects are mainly related to High Order Modes (HOM) in the RF cavities or ions effect such as ion trapping or fast-ion instability. Single bunch effects are mainly related to the Broad Band Impedance (BBI) of the ring and mainly manifest themselves as head-tail, Transverse Mode Coupling Instabilities (TMCI) and

Microwave Instability (MI). These effects generally produce a blow-up of the beam size or spoil the energy spread ultimately degrading the machine performance. In order to counteract them, several machines operate with high positive chromaticity, e.g. two units at Diamond. However this route can be followed to a limited extent since it compromises the nonlinear beam dynamics optimisation and spoils the dynamic aperture and the Touschek lifetime. Transverse Multibunch feedbacks (TMBF) are necessary for high current operation with zero chromaticity. TMBF system are in operation at Spring-8, SOLEIL, SLS, ELETTRA, and are under commissioning at Diamond.

SHORT PULSES PROGRAMME

Time resolved experiments use short radiation pulses to probe the time evolution of the reactions under study. In storage ring light source the photon pulse length is given by the electron bunch length in normal operating mode and the typical bunch length in modern third generation light sources ranges from 100 ps to 10 ps rms. The exploitation of such short pulses in pump-probe experiment requires a flexible timing systems which allows the implementation of few single bunches fill pattern or the so called camshaft fill pattern which render single bunch operation compatible with normal multibunch user mode.

In the last years it has become evident that that time-resolved science can benefit enormously of sub-ps radiation pulses. In order to extend the capability of the storage ring light sources to deliver a photon time structure useable for time-resolved science a number of schemes for the generation of ultra-short electron pulses have been devised. They can be classified in three main types

- shortening electron pulse length
- compressing the radiation pulse length
- energy modulation of a slice of the electron beam.

Shortening of the electron bunch is achieved by reducing the momentum compaction factor of the storage ring in the so called low-α optics. The short bunches generates are used for their enhanced coherent radiation in the THz region or by X-ray users. Experiments in this area have been pioneered at BESSY-II [29] recently followed by ANKA[30] ELETTRA[31] and SPEAR3. Commissioning of low-alpha optics is ongoing at SOLEIL and is planned in the near future at Diamond. Electron pulses as short as 0.7 ps rms were produced at BESSY-II although limited to low current per bunch limit due to the CSR instability.

A second method proposed by A. Zholents [32] is based on the use of transverse deflecting RF cavity to induce a chirp of the vertical position or momentum of the electron bunch and by the optical compression of the chirped photon beam emitted. A second RF cavity is necessary to cancel the effect of the transverse kick imparted by the first one and to avoid the blow-up of the vertical emittance. The number of straight sections that can benefit of the chirped electron beam depends on the users need and on the flexibility of the lattice. Several options have been put forward at APS, including pulsed normal conducting or CW superconducting operation. No experimental application of these schemes has been performed yet. Numerical studies at APS have shown that radiation pulses of the order of 1 ps FWHM with 10^4-10^6 photon per pulse of 4 keV photon energy can be achieved with 1% of the original photon emission intensity. Significant R&D is still required in order to damp the LOM and HOM of the crab cavities[33].

A third method to generate short radiation pulses is based on a scheme devised by A. Zholents, commonly called femto-slicing[34]. This scheme is based on the local energy modulation of the electron in a slice of the bunch, obtained by means of an external laser pulse copropagating with the bunch in a modulator wiggler. A dispersive section is then used to achieve either spatial or angular separation of the radiation emitted by the slice from the radiation emitted by the rest of the bunch. Femto-slicing sources are operational at ALS, BESSY-II and SLS while several other light sources have investigates possible implementation of this scheme. The pulse lengths achieved are 100 hundreds of fs FWHM with 10^5-10^6 photon/sec/0.1BW in the keV photon energy range[35]. Recent development at BESSY-II and SLS are based on the upgrade of the repetition rate of the laser to increase the photon flux[36].

TECHNOLOGICAL ADVANCEMENTS

The progress in the performance of third generation light sources has been possible due to many technological advancement in various areas, notably insertion devices which are crucial for medium energy rings but also RF system, BPM and Power Supplies.

The advancement in the IDs technology over the last decade has extended the capabilities of the storage ring light source in many directions. In-vacuum IDs are now used in many light sources. The extremely good field quality of the undulators, operating at gaps as low as 5 mm, allows higher brilliance and substantial photon emission on higher order harmonics reaching photon energies as high as few keV also in medium energy storage rings with average brilliance of 10^{20} ph/s/0.1%BW/mm^2/mrad^2. High energy machines such as APS, ESRF, SPRING8 using undulators reach even higher brilliance up to few tens of keV photon energy. Elliptically polarised undulators are extensively used at new synchrotron light sources. Apple-II type undulators are used at ELETTRA, SLS, Diamond, SOLEIL, BESSY-II. Fast polarisation switching experiment have become possible at SPRING8 and SLS and are under consideration at other light sources.

Recent advancements are given by cryo-cooled permanent magnet undulator (150 K) which allow the increase of the magnetic field up to 30% [37-38] achieving larger K values for the same gap and period. This increases the photon emission at higher harmonics extending the photon energy range, the brilliance and the tunability. The development of Nb_3-Sn based superconducting undulators promise to extend even further the capabilities of IDs[39].

UPGRADE PROGRAMMES

Storage ring light source continuously strive to match the increasingly complex users' demands. Furthermore, many established light source are also trying to keep up with the increased performance of recently commissioned ones. For this reason a series of upgrade programmes are actively pursued. Few example are given below.

ESRF has launched an upgrade programme that will cover its scientific and technological needs for the next ten years [40]. While the lattice upgrade to a reduced horizontal emittance was considered too demanding, in terms of shutdown time and re-commissioning, higher flux can be obtained with longer straight sections (from 5 to 6 m) simply by removing the final quadrupoles at each end of the straight sections. Even longer straight sections (7 m) can be obtained if shorter quadrupoles are used. A second improvement consists in the increase of the stored current from 200 mA to 300 mA which would entail an RF upgrade towards solid state amplifier technology and normal conducting HOM damped cavity at 352 MHz. Top-Up operation will be pursued for few single bunch modes and will allow operation at lower vertical emittance. These measures, together with a lower coupling operation, will allow increasing the brilliance by more than a factor of two in the tens of keV region.

APS has an ambitious upgrade plan based on a ERL concept[41]. At the same time intermediate upgrade options have been examined and they involve increase of the current from 100 mA to 200 mA, lengthening of the straight section, allowing longer IDs or canted undulators, the crab cavities short pulse programme and the improvement of the fast orbit feedback with the long term goal to achieve 5 % of beam size and divergence up to 200 Hz. Recently commissioned machine like Diamond and SOLEIL have already undergone a number of improvements since they begun users' operation. Diamond has an operating FOFB system [42], a TMBF under commissioning and future plans include moving to Top-Up operation, delivering the nominal 300 mA in users operation, the implementation of low-alpha optics, customised optics in dedicated straight sections, canted undulators and the further diversification of the IDs portfolio including a CMPU. Very similarly, SOLEIL has a TMBF system in operation [28] a FOFB is under commissioning, Top-Up operation is planned by the end of 2008, 500 mA in multibunch and 100 mA in 8 bunches will soon be delivered to users. Plans are in place to implement low-alpha optics and a femtoslicing experiment. The diversification of the IDs include also the CMPU[43].

CONCLUSION AND ACKNOWLEDGMENTS

Third generation light sources provide a very reliable source of high brilliance, stable X-rays. There is no evidence of under-subscription at the various facilities: the user's community and the number of beamlines is increasing. Further developments are targeting even higher brilliance, higher stability, short pulses, high current and larger capacity.

Finally, the contribution of many Accelerator Physicists to this review is warmly acknowledged.

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