ACCELERATOR PHYSICS CHALLENGES IN THE DESIGN OF MULTI-BEND-ACHROMAT-BASED STORAGE RINGS

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Abstract

With the recent success in commissioning of MAX IV, the multi-bend achromat (MBA) lattice has begun to deliver on its promise to usher in a new generation of higher-brightness synchrotron light sources. In this paper, we begin by reviewing the challenges, recent success, and lessons learned of the MAX IV project. Drawing on these lessons, we then describe the physics challenges in even more ambitious rings and how these can be met. In addition, we touch on engineering issues and choices that are tightly linked with the physics design.

INTRODUCTION

Third generation storage ring light sources brought unprecedented X-ray brightness and flux from insertion device photon sources to the synchrotron radiation scientific community. However a growing number of applications would benefit from even higher brightness beams and their enhanced transverse coherence, including nanometer imaging applications, X-ray correlation spectroscopy and spectroscopic nanoprobes, diffraction microscopy, holography and ptychography.

Given that photon spectral brightness B(λ) is inversely proportional to the convolved photon-electron emittance $\Sigma_{x,y}(\lambda)$ at wavelength λ for each transverse plane x and y (i.e. $B(\lambda) \propto (\Sigma_x(\lambda)\Sigma_y(\lambda))^{-1}$, $\Sigma_{x,y}(\lambda) = \varepsilon_r(\lambda) \oplus (\varepsilon_{x,y})$), there is an ongoing effort to reduce electron emittance in storage ring light sources towards the diffraction limited photon emittance $\varepsilon_r(\lambda)$ (= ~λ/4π to ~λ/2π, depending on photon source properties, or ~8 pm-rad to 16 pm-rad for λ = 1Å) for wavelengths of interest to reach maximal brightness. Along with the increase in brightness, the percentage of transversely coherent photons also increases as electron emittance is reduced, approaching a maximum of 100% when the electron emittance drops below $\varepsilon_r(\lambda)$.

While diffraction limited emittance for angstrom-wavelength X-rays can be routinely reached in the vertical plane by reducing the horizontal-vertical emittance coupling to very small values, the horizontal emittance for 3rd generation machines is typically in the 1- 10 nm-rad range. This level of emittance is the result of the typical implementation of double- and triple-bend achromat (DBA and TBA) lattices using storage technology that has been developed over a few decades. However it is known that the emittance of a storage ring scales as $F(\nu,\text{cell})E^2(N_sN_d)^{-3}$, where F(ν,cell) is a function of ring tune ν and lattice type, E is the electron energy, and N_s lattice sectors (with intervening insertion device straight sections) each have N_d dipoles. For a given lattice cell type, a larger ring circumference C will accommodate more sectors and emittance is reduced by C^{-3}. Light source lattice cells are typically achromatic, or nearly so, to minimize the increase in effective beam emittance in ID straights caused by electron energy spread.

The concept of increasing N_d to create multibend achromat lattices is not new [1], but it is only in the last several years that developments in precision magnet design, vacuum technology and advanced tools for simulating and optimizing highly nonlinear lattice designs have been made to actually build rings having affordable size (i.e. of order 1 km for 6 GeV, 0.5 km for 3 GeV, and 0.2 km for 2 GeV) with emittances substantially lower than the 3rd generation. The 3-GeV, 528-m MAX IV ring, discussed below, is the first pioneering implementation of such a "4th generation" storage ring light source, having a 7-bend achromat (7BA) lattice having the order of 300 pm-rad emittance that is now in operation, and in construction is the Sirius Light Source in Brazil with a 5BA lattice and similar size and emittance to MAX IV. In the meantime the high energy ESRF and APS light sources are in the process of upgrading their lattices to modified 7BA lattices, exploiting longitudinal gradient dipoles to obtain further emittance reduction, and in the case of the APS, using a "reverse bend" design [2,3] for a reduction in emittance to 41 pm-rad (the diffraction limit for 2.5-5 Å photons) at 6 GeV. Other facilities, including SPring-8, ALS, SLS and others also planning lattice upgrades sometime in the future, while IHEP is planning a new MBA ring comparable in size and performance to the APS and SPring-8. In the case of the APS and the ALS (a 9BA lattice), emittance is reduced to the point that the dynamic aperture will not support off-axis injection with accumulation; on-axis "swap-out" injection will be used. In the future, given that the science case is justified, rings having ~2-km circumference might be built having order 10 pm-rad emittance (e.g. PETRA-IV at DESY).

The physics and engineering challenges associated with implementing these state-of-the-art 4th generation light sources are daunting and are discussed in the following.

LESSONS OF MAX IV

Commissioning of the MAX IV 3 GeV storage ring started in August 2015 and is ongoing. A report of the commissioning status can be found in [4]. Here we only summarize a couple of key issues relevant to the design and commissioning of future MBA-based storage rings.

Magnets & Alignment

The MAX IV 3 GeV storage ring relies on the magnet block concept [5] where the various magnets contained in one cell are machined from two solid blocks of iron that then act as upper and lower magnet yoke halves. These halves are then joined around the vacuum chamber [6] and serve, together with a solid concrete support, as the magnet girder, thereby ensuring relative alignment of adjacent magnets as well as vibrational stability. This concept has allowed MAX IV to substantially reduce the amount of in-house work required for installation and alignment. The internal alignment of the magnetic centers of adjacent magnets within the block is on the order of only a few micron [7], while the laser tracker alignment of individual blocks with respect to neighboring blocks can be performed to better than 50 micron.

An important consequence of this high degree of alignment, was that the first turn in the MAX IV 3 GeV storage ring was achieved without excitation of a single corrector and all magnets set to nominal settings, i.e. using currents according to the results of magnetic bench measurement data. Considering that the inside diameter of the circular vacuum chamber is only 22 mm and that the sextupoles are fairly strong [8, 9], this is quite remarkable. It does, however, emphasize the importance of high-quality field mapping, especially for gradient dipoles. Furthermore, careful modeling of magnets, most importantly for magnets with longitudinal gradients, is crucial.

Instrumentation

Achieving first turns in the MAX IV 3 GeV storage ring also relied heavily on a high-resolution BPM system with single-pass read-out capabilities. 200 button BPMs connected to Libera Brilliance+ units allow for a very fine sampling of betatron oscillations in both planes. During the earliest stages of commissioning, the single-pass read-out provided sum signals that could be used as relative loss monitors around the machine. The raw ADC buffers were used for corrector tuning when attempting to increase the number of turns. Since betatron motion is oversampled individual BPMs can also be connected to an oscilloscope or spectrum analyzer. The former provided a simple and inexpensive fill pattern monitor, while the latter is routinely used in order to measure the synchrotron tune parasitically and to high accuracy. While most BPM units performed very well during early commissioning, throughout the entire campaign we nevertheless encountered various difficulties mainly connected to communication through the Tango control system and control via the Tango device drivers.

Vacuum System

The MAX IV 3 GeV storage ring relies on a circular copper vacuum chamber with NEG-coating and a standard inside diameter of 22 mm [10]. This allows for small magnet gaps and a very dense magnetic lattice, both prerequisites for successful MBA lattice implementation [11]. Since the chamber itself acts as a distributed absorber, it needs to be cooled from the outside through a cooling channel. The NEG coating is required in order to efficiently achieve and maintain UHV conditions in this narrow system despite its low pumping cross sections. So far, the NEG-coated copper vacuum system has met the challenge. Normalized pressures well below 1e-10 mbar/mA were already achieved after 10 A h dose was accumulated. At the time of writing, 100 A h of dose have been surpassed and average pressures are still decreasing exponentially. Along with the improving pressures, the overall beam lifetime is still increasing. As 100 A h dose was achieved, $I \times \tau$ in excess of 1 A h was reached. There is still a very clear monotonic increase of lifetime with dose indicating that vacuum conditioning is still ongoing. Presently, $I \times \tau$ beyond 3 A h has been recorded and no signs of saturation have been detected as we approach the design goal of 5 A h. The copper vacuum system is however very delicate. Throughout the arc it is aligned very well by the tight spacing in the magnet blocks. In the long straights, however, it can easily be deformed leading to misalignment with respect to the magnetic lattice and the stored beam. Ensuring proper fixation in these areas is important to prevent beam loss and perhaps more importantly, heating of uncooled chamber areas which otherwise becomes a serious limitation when increasing stored current.

RF & Bunch Length

The MAX IV 3 GeV storage ring makes use of a 100 MHz main RF system with passive harmonic cavities at the third harmonic. Since the MAX IV Short Pulse Facility located on the 3.4 GeV MAX IV linac can accommodate users requiring short pulse duration, the MAX IV storage rings could be optimized for longer bunch lengths. In combination with the added Landau damping from the harmonic cavities, this results in a reduction of instability thresholds (reduced overlap between machine impedance and narrow bunch spectrum), reduced RF heating, increased Touschek lifetime as well as a reduction of emittance blowup caused by IBS at 500 mA stored current. Furthermore, at 100 MHz a very low cavity voltage is required (1.8 MV) to achieve a high RF acceptance (7%) which allows taking full advantage of the large lattice momentum acceptance provided by the nonlinear optics design [8, 9, 12]. This low voltage and highly efficient amplifiers at 100 MHz lead to a substantial reduction of the required power and hence running cost.

Both 100 MHz main cavities and 300 MHz Landau cavities have been designed in house [13, 14]. Six 100 MHz room-temperature copper cavities, manufactured by RI, have been installed in the MAX IV 3 GeV storage ring. They are of capacity-loaded type and can sustain 300 kV of maximum gap voltage. Each cavity is powered by its own solid-state amplifier from R&S. These amplifiers currently provide 60 kW per cavity which we plan to extend to 120 kW once the ring is more heavily loaded with IDs. The efficiency of these amplifiers is at a comparably high 66%. In general, amplifiers for 100 MHz are widely available and inexpensive. Three passive Landau cavities (LCs) at 300 MHz have been built in house and installed in the MAX IV 3 GeV storage ring. These LCs can stretch bunches by roughly a factor five compared to natural bunch length. With their shunt impedance of ~2.5 MΩ, three of these LCs allow reaching flat-potential conditions for currents as low as ~150 mA.

The resulting long bunch lengths significantly increase Touschek lifetime. Roughly 25 hours of Touschek lifetime are required at 500 mA in order to reach the overall 10 hour lifetime goal. It is the large longitudinal acceptance that allows for high Touschek lifetime even at ultralow emittance. In fact, if enough momentum acceptance can be ensured, Touschek lifetime can start to increase as the lattice emittance reduces. This unusual behavior is a novelty in modern MBA lattice-based storage rings where the power radiated in the dipoles is very low compared to the overall radiated power which ultimately determines the equilibrium emittance [12]. However, the resulting long bunch lengths also reduce the emittance blowup from IBS, which is very strong at medium energy and high stored current. As more IDs are added to the MAX IV 3 GeV storage ring, the zero-current emittance will further reduce and the emittance blowup from IBS will accordingly increase. It is only the long bunches that can hold this in check thereby preserving the ultralow emittance even when large amounts of current are stored [12].

The baseline design of the MAX IV 3 GeV storage ring foresees an even multibunch fill without ion clearing gap (no such gap was required at the 100 MHz MAX II and MAX III storage rings). Since gaps in the multibunch fill pattern can severely perturb the phase and amplitude of the fields excited in the passive LCs, ensuring an even multibunch fill is strongly connected to achieving the necessary bunch lengthening and capture efficiency [15, 16]. Consequently, this means no special fill patterns (e.g. camshaft bunches, hybrid modes, etc.) were to be provided to users in the baseline design. However, during the last two years the MAX IV user community has started compiling a science case for timing experiments in the MAX IV storage rings [17]. There is an ongoing accelerator physics research project [18] dedicated to developing solutions that will allow for timing experiments in the MAX IV storage rings, while ensuring that perturbations of the stored beam related to the passive LCs are minimized.

Injection

Injection into the MAX IV 3 GeV storage ring during commissioning has relied on an injection scheme based on a single dipole kicker [19]. In this setup the dipole kicker can be used for both on-axis as well as off-axis injection. It can in fact even accumulate beam by sharing a reduced kick strength between the injected bunch and any already stored bunches. Although this strongly excites the stored beam (and is hence not compatible with transparent top-off injection during user shifts), it has proven perfectly capable of accumulating large stored current. The setup, including a Ti-coated ceramic chamber, ferrite kicker magnet, and pulser assembly was manufactured by BINP and has proven robust and reliable. Until now, high capture efficiency (~96%) has been demonstrated in the storage ring using this single dipole kicker. Quite obviously, the low injected emittance from the full-energy MAX IV linac in conjunction with a comparably large storage ring acceptance are very well matched to this injection scheme. We foresee that this setup will allow us to go well beyond the so far accumulated 198 mA in order to continue commissioning. The dipole injection kicker has also allowed running in top-off mode (so far only with closed shutters) where shots from the linac are injected every few minutes into the MAX IV 3 GeV storage ring thus allowing for constant levels of stored current for e.g. vacuum conditioning over nights and weekends. The multipole injection kicker [20, 21] that should in the future allow for transparent top-off injection is presently being manufactured within a collaboration between MAX IV, SOLEIL, and HZB. Its delivery is expected during early 2017.

PHYSICS CHALLENGES

As the experience of MAX IV illustrates, there are many physics challenges in pushing beyond 3rd generation light sources. Among these are more difficult nonlinear dynamics, collective instabilities, new injection methods, control of intrabeam scattering, improvement of beam lifetime, etc. In this section we touch upon these issues and indicate how they are being addressed for the Advanced Photon Source Upgrade (APS-U) [22].

As described above, reduction of the emittance requires stronger, more frequent focusing. Analysis based on TME cells [23] shows that the quadrupole strength scales like N_d^2. This increases the natural chromaticity and reduces the dispersion. As a result, the sextupole strengths scale like N_d^3, leading to strong high-order aberrations. This is turn leads to reduce dynamic acceptance (DA), which makes injection more difficult. It also leads to reduced local momentum acceptance (LMA), which makes the Touschek lifetime shorter. Both lead to shorter gas scattering lifetime.

Although nonlinear dynamics is challenging, recent advances provide many avenues to success, beginning with the choice of lattice structure. The MAX IV lattice, consisting of central TME-like cells with dispersion suppressors, relies on having a large number of independent sextupole and octupole families. For future high-energy rings in particular, a different approach seems recommended. For example, the hybrid MBA lattice [24] developed for ESRF provides two high-dispersion areas in each cell, wherein the sextupoles are placed. This results in sextupoles that are weaker by a factor of 3-4 [25]. By arranging a specific phase advance between these sextupoles, partial cancellation of geometric aberrations is achieved. The lattice design for PEP-X [26] also makes use of specific phase advance to cancel harmful aberrations. Experience shows that various approaches can then be used to improve the performance, the most popular being tracking-based multi-objective genetic algorithms (MOGA) [27-32].

After exploration of various alternatives [25], APS-U has settled on a variant of the hybrid seven-bend-achromat [24]. To further reduce the emittance, conversion of six quadrupoles per sector into reverse-direction bending (RB) magnets [2, 3] is under study [33]. This increases the damping rates, changes the damping partition, and allows more independent manipulation of the beta functions and dispersion, resulting in an emittance of 41 pm and a 50% increase in x-ray brightness compared to having no RBs.

Once a lattice has been optimized, it is important to assess its robustness. In the case of APS-U, we are particularly concerned with the ability to commission the lattice quickly, since we plan a 12-month shutdown for replacement of the ring and returning to operations. Hence, we have developed a simulation of the commissioning process [34], including injection tuning, establishing the closed orbit, establishing stored beam with workable lifetime, and measurement and correction of BPM offsets and optics. The simulation is executed for 100 or more random error sets. Tracking is then performed for each corrected configuration, providing the DA, LMA, injection efficiency, etc. [35, 36]. As shown in Fig. P1, the DA is expected to be quite small, but still large enough for on-axis injection. Achieving larger DA is possible, but only at the expense of lower brightness [25].

Many 3rd-generation rings were built at a time when simulation tools did not provide a reasonable means of assessing collective instabilities. However, experience with modeling the existing APS storage ring indicates that accurate prediction of collective instabilities is possible [37]. When applied to the APS-U lattices, this approach has led to the surprising conclusion that accumulation of intense bunches is highly problematic [38]. This further solidifies the decision to embrace on-axis swap-out injection [39, 40] as the operating mode. This puts an increased burden on reliability and performance of the injector [41, 42].

In addition to collective instabilities, other collective effects are of concern, namely, intrabeam scattering (IBS) and Touschek scattering. IBS can potentially undo some of the beneficial effects of the lattice optimization and fights the beneficial E^2 scaling of the natural emittance. Mitigating strategies include bunch- lengthening, many bunch fills, large vertical emittance, and high beam energy. Analysis for APS-U indicated that the optimum beam energy is between 6 and 7 GeV, depending on whether one emphasizes softer or harder x-rays. 6 GeV was chosen based on the APS emphasis on hard x-rays and the engineering difficulty of higher energy.

Mitigating strategies for Touschek lifetime challenges are similar to those used for IBS. Hence, APS-U nominally employs a 4th-harmonic passive bunch-lengthening cavity and runs with “round” beams ($\varepsilon_y=\varepsilon_x$). Inspired by MAX IV, use of ~100-MHz rf systems [43] is also under study [P14]. These seem quite effective in lengthening Touschek lifetime, suppressing IBS, and also suppressing the longitudinal microwave instability.

ENGINEERING CHALLENGES

What is the state of the art in alignment, magnet strength, vacuum systems. How does this make the physics challenges easier. If we could push the engineering, could we envision even brighter rings?As already noted, there have been a number of impressive engineering developments that have been fundamental in the success of MAX IV. One of the most significant is NEG coating vacuum chamber technology. This is now a well-established industrial technology that has been extensively used at LHC, SOLEIL and now MAX IV. MAX IV is the first that was nearly 100% NEG coated.

Despite the success of MAX IV, there remain many engineering challenges that need to be addressed particularly for MBA storage ring light sources that are being developed and are pushing even further towards the diffraction limit. This includes

- even higher gradient magnets
- improved beam stability
- fast injection elements for swap-out injection
- small <10mm diameter insertion device and complex geometric NEG vacuum chambers
- novel insertion devices
- superbends for harder x-ray sources
- coherence preserving optics

Many of these challenges have been addressed in other papers [44] Here we will expand on a few of the engineering challenges: injector technology, specialized radiation production magnets, and vacuum technology.

With the goal of increasing the brightness and coherent flux, MBA storage rings are moving to more aggressive, stronger focusing lattices to achieve ever-smaller emittances. These smaller emittances coupled with smaller beta functions result in smaller transverse dynamic apertures that, in some cases, are not compatible with traditional off-axis accumulation. For instance some projects (APS-U and ALS-U) are adopting lattices with only 1 or 2 mm of dynamic. This presents a challenge and an opportunity. On axis injection is compatible with operating with full coupling and small beta straights both of which are advantageous for further emittance reduction, mitigating the effects of Intrabeam scattering, maintaining lattice symmetry and the inclusion of higher performance insertion devices.

With on-axis swap-out injection, a bunch or a train of bunches in the storage ring is replaced with a fresh bunch or bunch train without perturbing the neighboring bunches. The challenge is the injection kicker and pulser technology where the rise and fall times and pulse shapes determine the fill patterns that are compatible with swap-out. With lower frequency RF systems, such as 100 MHz, there should be no restriction on fill patterns to accommodate the rise and fall times however gaps in the fill patterns may be necessary to accommodate the rise and fall times for higher frequency RF systems such as 350 and 500 MHz.

In the case of ALS-U and APS-U, typical timing specifications are from 5 to 10 ns with flat tops ranging from ns (for bunches) and up to 50 ns (for bunch trains) with voltage requirements range from 6 kV (ALS-U) to 20 kV (APS-U). Currently there are three pulser technologies being pursued: FID [45], inductive [46], and transmission adder technologies [47]. The bench testing results are very promising and plans are in place to install strip line kickers for beam testing [48].

Operating with on-axis swap-out injection enables optimization of insertion devices beyond what is possible on current rings. In general, apertures can be smaller, enabling higher fields or shorter periods. In addition, it will be possible to make the horizontal aperture in undulators very small as well, enabling new classes of undulators. Such undulators promise ultimate performance for experiments requiring polarization control. Possible candidates include superconducting helical undulators [49] or Delta-type [50] permanent magnet undulators. Development would include the necessary very small round aperture vacuum chambers [51], dealing with heating / synchrotron radiation absorption, beam dynamics optimization for the unusual off-axis fields always present in Delta undulators, as well as optimization of cost and shimming methods.

In addition to using the premier undulator sources, many light sources have large community utilizing bending magnet sources from IR to harder x-rays. For example presently roughly half of the ALS beamlines sources are bending magnets. The spectrum for many of these beamlines is in the tender or hard x-ray region. One potential disadvantage of fully optimized multi-bend achromat lattices is the relatively low bending field resulting in a fairly soft spectrum of bending magnets. This is especially true for light sources using lower electron beam energies (2 to 3 GeV). To continue to serve this community, several possible solutions that could be inserted into a standard arc including compact superconducting dipoles [52, 53] or permanent magnet [54] high field dipoles. One of the challenges is shaping the field and optimizing the lattice in such a way that these sources do not significantly increase the beam emittance.

In terms of vacuum technology, one of the potential weaknesses of the first deployment of NEG-coated chambers for almost 100% of an accelerator (MAX IV) is the need to activate the chambers (typically to about 180 degree C) outside of the accelerator. This limitation can be overcome with in-situ activation. Possible solutions include very space efficient heaters that do not require large stand-clears for the accelerator magnets surrounding the vacuum chambers. These heaters need to address thermal shielding challenges, since permanent magnet undulators, as well as epoxy coils, can be damaged by excessive heating. There has already been extensive development at SIRIUS [55]. In-situ activation has many challenges including radiation hardness, thermal conduction/temperature uniformity, susceptibility to heater damage, unwanted heating of the surrounding magnets and supports, space needs, and how to deal with chamber expansion during the activation.

CONCLUSION

Storage ring light sources are arguably the most productive large-scale research facilities in existence. Ultra-low emittance electron storage rings open up new avenues for x-ray research. Multibend achromat lattices are the key to delivering the next generation of these storage rings. In such machines, we expect more than two orders of magnitude increase in brightness compared to 3rd generation rings. A world-wide effort is underway to either build new facilities based on MBAs or upgrade existing rings to employ MBA lattices. The success of MAX IV has demonstrated that MBA lattices are feasible. There remain several exciting physics and engineering challenges connected to new MBA-based sources, however, no show-stoppers have yet been recognized on the path to fully diffraction-limited light sources. It remains to be pointed out that while the first MBA concepts were developed in the early 1990s, only now are operational facilities based on this concept coming online. It is therefore time to start developing ideas for the light sources we want to operate 25 years from now.

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