

LATTICES FOR A 4TH-GENERATION SYNCHROTRON LIGHT SOURCE

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Abstract

Inspired by light source upgrades, such as ESRF-EBS (Extremely Brilliant Source) and APS-U, I present some modern lattices for a medium-sized 4th-generation synchrotron radiation source. They incorporate new elements, such as anti-bend magnets. The composed lattices are optimized using a simple double-objective algorithm. Its goal is to minimize the natural emittance and absolute chromaticities simultaneously. Then, the lattices are analyzed and compared to a version of the ESRF-EBS lattice scaled down in size. The design is performed to meet the needs of the user community of the Siberian Synchrotron and Terahertz Radiation Centre under the umbrella of the Budker Institute of Nuclear Physics.

INTRODUCTION

Synchrotron radiation (SR) is a widely applicable tool for matter analysis in cutting-edge science, technology and medicine. Driven by diverse applications in X-ray crystallography [1], a number of large SR-facilities was built around the world. Thanks to invaluable radiation properties, scientists in other research areas became users as well [2, 3]. For more examples and details, see, for instance [4].

In this paper, I design and compare lattices for a specialized synchrotron light source of the 4th generation. It is supposed to provide access to modern research techniques using SR for the users of the Siberian Synchrotron and Terahertz Radiation Centre, institutions of Siberian Branch of Russian Academy of Sciences and Siberian region overall.

Currently, the accelerator system that delivers SR is operated by the Budker Institute of Nuclear Physics (BINP) and comprises: VEPP-4M collider (commissioned in 1979, upgraded in 1994), its predecessor and booster, VEPP-3 (commissioned in 1971, upgraded in 1987). They are the last synchrotron light sources of the 1st generation in the world (designed not as light sources, operating in the parasitic mode). A modern source with competitive parameters (see Fig. 1) would allow current users to widen the range of their investigations and attract new users to the community.

As requested by the user community, the prospective light source should have: energy of electrons at 3 GeV to provide flexible spectrum hardness for most applications and natural emittance below 1 nm-rad to deliver high brilliance, comparable with the 4th-generation light sources (for example, MAX IV). This implies additional technical requirements:

- moderate storage ring circumference about 300-320 m,
- high average electric current (e.g. 200 mA),
- long straight sections (not less than 10) with zero dispersion for insertion devices (ID) accommodation,

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- appropriate conditions for top-up injection from a booster synchrotron (sufficient dynamic aperture, momentum acceptance, horizontal beta-function increase and Touschek lifetime).

LATTICE DESIGN

The main challenge is to attain ultra-low emittance in a moderate circumference with feasible parameters of lattice elements. To achieve it, let us recall existing lattice solutions:

- Conventional *multi-bend acromat* (MBA) to construct long straight sections with zero dispersion and approach the *theoretical minimum emittance* (TME) [6],
- *Anti-bends* (strongly focusing dipole magnets with a small negative bending angle) within the lattice provide better matching by disentangling dispersion and horizontal beta-function and reduce the emittance via impact on the damping partition number J_x [7],
- $-I$ transformation between sextupoles invokes cancellation of nonlinear aberrations [8],
- *Raimondi lattice* introduces regions of increased dispersion for low emittance arcs where it is insufficient for feasible chromaticity correction [9].

Preliminary lattices based on these solutions were created with OPA lattice design code [10]. In the TME cell with $-I$ transformation, absolute values of chromaticity are considerably higher than in others and the emittance minimization conflicts with the $-I$ condition. Thus, the $-I$ transformation should not be used separately, but within a lattice of another kind. For instance, MAX IV lattice is MBA and ESRF-EBS lattice is of Raimondi type, but both implement $-I$ transformation to cancel out the 1st order aberrations. For more detailed analysis, I composed the following lattices:

- An anti-bend MBA arc with the $-I$ transformation between sextupoles (Fig. 2, a),
- A Raimondi MBA arc, similar to the ESRF-EBS lattice scaled down in size (for comparison, Fig. 2, b),
- A Raimondi MBA arc with anti-bends and the $-I$ transformation between sextupoles (Fig. 2, c).

At first, I also considered a Raimondi MBA arc with anti-bends instead of quadrupoles. Although in linear optics it did show promising results, with non-linear effects included, the dynamic aperture was not sufficient for the injection.

The next step is the numerical optimization of the lattices in order to decrease the emittance while keeping absolute chromaticities at rather small values. This idea was realized in a simple double-objective algorithm based on the matching function in MAD-X [11]. I used a control loop for the emittance and chromaticities and the matching function to construct a penalty function for minimization. Since

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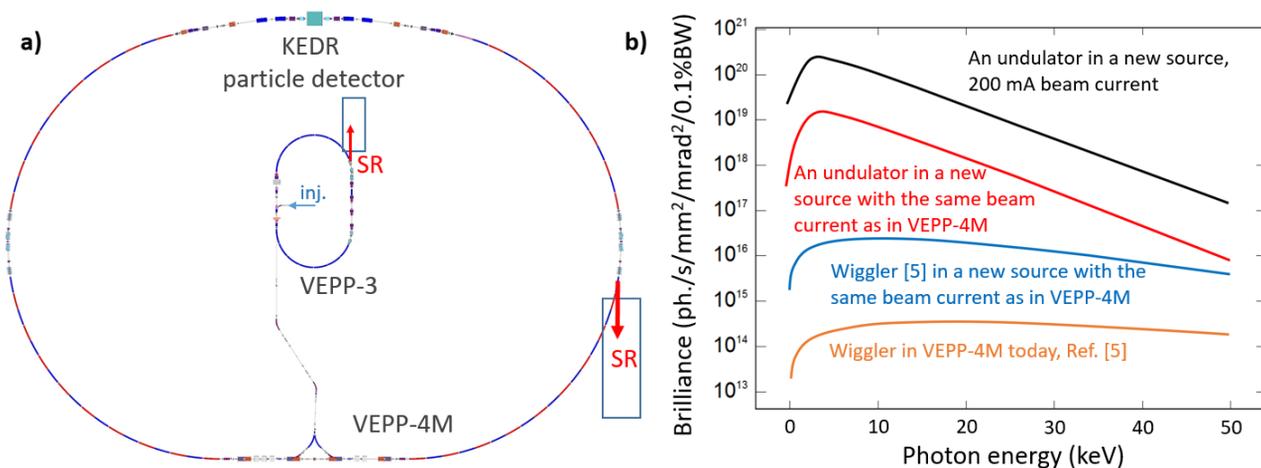


Figure 1: **a)** Layout of existing synchrotron light sources at the SSTRC (BINP). **b)** A comparison of the brilliances achievable by a new source with today's values [5]. Brilliances of an undulator (1 T, 1 m, 15 periods) are depicted as envelopes.

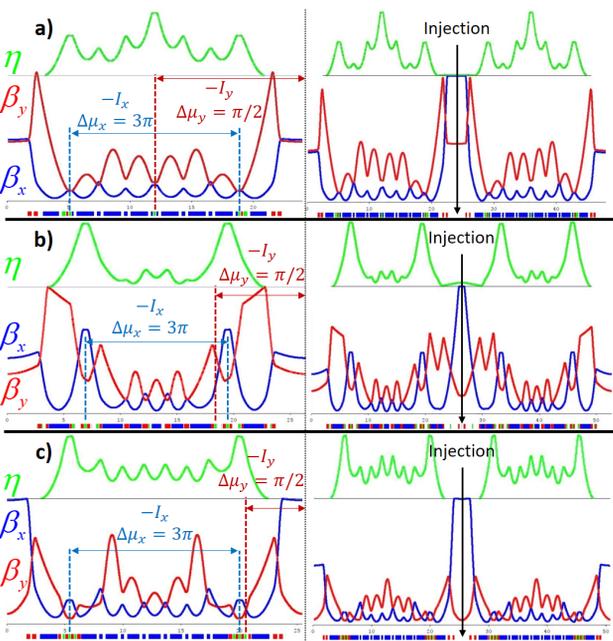


Figure 2: Structural functions of numerically optimized lattices: **a)** $-I$ & ab arc, **b)** R & $-I$ arc, **c)** R & $-I$ & ab arc. Dashed insets show the positions of $-I$ sextupoles and phase advances between them; in the y -plane, the condition is fulfilled with adjacent arcs. The right-hand side column shows the disturbed arcs to accommodate the injection point.

zero-dispersion sections are necessary, the related parameters are exempt (at ID locations $\alpha = 0$, $\eta = 0$, $\eta' = 0$). A typical runtime of the algorithm on a common laptop is 10-15 minutes. The lattices presented in Fig. 2 are already optimized by this algorithm. For electron beam injection, I designed the disturbed arcs (Fig. 2, the right column) with a higher value of the horizontal beta-function adjacent to the injection location. For this, the algorithm was modified to maximize this β_x value with additional constraints to match with the arcs of the main lattice.

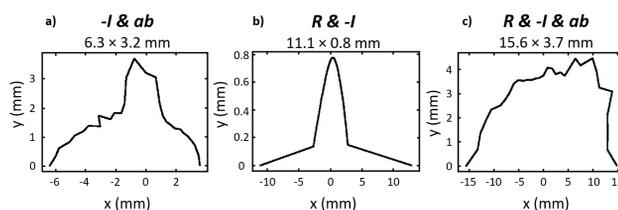


Figure 3: Dynamic apertures in the complete storage rings: **a)** $-I$ & ab arc, **b)** R & $-I$ arc, **c)** R & $-I$ & ab arc.

The following tracking (1000 turns) of dynamic apertures at the injection point of each ring is performed using a symplectic function in Elegant [12] (see Fig. 3). Since the injection of electrons is supposed to be from a booster synchrotron inside the storage ring, negative x -values of aperture are taken into consideration [13]. Resulting parameters of complete storage rings are presented in Table 1.

All three lattices contain non-traditional elements: R & $-I$ employs bending magnets with a longitudinal gradient, as in the ESRF-EBS [9], both $-I$ & ab and R & $-I$ & ab comprise anti-bend magnets.

The simplest way to make such an anti-bend is to realign a quadrupole lens (Fig. 4, a). However, it would be sensitive to misalignments, thus, other concepts should be investigated. A dipole-quadrupole designed for the ESRF-EBS (Fig. 4, b) is a similar magnet, but has regular positive bending angle [9]. Another auspicious idea described in Ref. [7], is to create the anti-bend field distribution in a half-quadrupole with a reflective panel.

CONCLUSION

A survey of the resulting parameters (Table 1) gives ground to conclude that the combined lattice (R & $-I$ & ab) excels over the two others in terms of the most important parameters: the emittance and the dynamic aperture. Additionally, the field gradients required in its elements are rather moderate. The $-I$ & ab lattice might still be of interest,

Table 1: Comparison of Storage Ring Parameters

Parameter	$-I$ & ab	R & $-I$	R & $-I$ & ab
Circumference	287.76 m	316.49 m	305.25 m
Emittance (including intra-beam scattering)	607 pm-rad	627 pm-rad	540 pm-rad
Betatron tune x/y	27.57 / 6.67	28.61 / 10.22	26.24 / 18.20
Natural chromaticity, x/y	-37.75 / -39.16	-41.01 / -30.53	-36.87 / -35.54
Corrected chromaticity, x/y	+1.04 / +1.02	+0.99 / +1.00	+0.95 / +1.08
Momentum compaction factor	$0.8 \cdot 10^{-3}$	$0.6 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$
Dynamic aperture (with a transverse beam size σ)	6.3 mm, $\approx 50 \sigma$	11.1 mm, $\approx 90 \sigma$	15.6 mm, $\approx 135 \sigma$
Momentum acceptance	+3% / -2%	+4% / -5%	+3% / -2.3%
Touschek lifetime (180 MHz RF, 10 mA/bunch)	≈ 19.6 hours	≈ 38.5 hours	≈ 23.8 hours
Energy loss per turn	349.6 keV	436.2 keV	410.2 keV
Space reserved for insertion devices	11×3.4 m	11×5.3 m	11×3.4 m
Space reserved for the injection system	2.9 m, $\beta_x = 34$ m	2×1.4 m, $\beta_x = 22$ m	2.6 m, $\beta_x = 25$ m

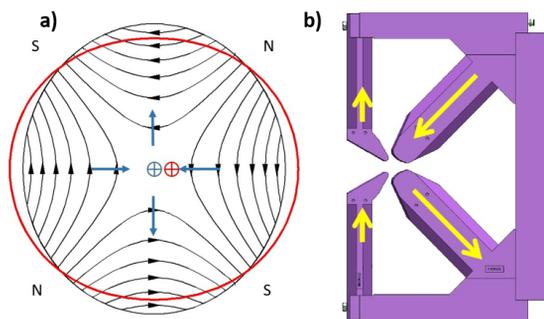


Figure 4: Approaches to design an anti-bend magnet. **a)** Quadrupole lens-based: blue arrows show focusing and defocusing forces, blue cross shows the position of the electron beam in the lens, realigning the beam towards the red cross gives the anti-bend field distribution; **b)** Similar combined-function magnet designed for the ESRF-EBS.

anticipated for more compact storage rings, but it requires a much more cumbersome tracking-based optimization to increase the dynamic aperture and constrain field gradients. The R & $-I$ lattice is similar to that of the ESRF-EBS scaled down in size and is presented mainly for comparison. A light source based on the combined R & $-I$ & ab lattice would be appropriate to produce high-brilliance synchrotron radiation for the user community in Siberia and Russia overall.

The algorithm used in the design has proved to be an efficient tool for quick estimates of performance for different lattices. Nevertheless, finalizing the design requires tracking-based optimization with a multi-objective genetic algorithm.

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