Candidate injector design for SAPS based on linac and booster

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Abstract

The Southern Advanced Photon Source (SAPS) is a diffraction-limited synchrotron light source under design, which employs longitudinal injection as its primary injection scheme. This kind of injection scheme requires that the injected beam has a short bunch length and low emittance, and the preferred injector should offer high stability and low costs. Therefore, the injector based on booster synchrotron is developed. This proposed injector includes a 250 MeV Linac, a booster synchrotron that ramps beam energy to 3.5 GeV, and two beam transport lines to ensure efficient beam delivery and beam quality preservation. The Linac utilizes a thermionic high-voltage DC gun for reliable operation and features a bunching system with an advanced focusing system to preserve emittance. In order to meet the injection requirements of the SAPS, a comprehensive design for the booster has been conducted. The booster synchrotron employs a three-fold lattice structure, incorporating modified theoretical minimum emittance cells with a small momentum compaction factor and a high voltage to achieve an emittance of 3.98 nm.rad and a bunch length of 4.8 mm. The injector has the potential to deliver a high charge, reducing the injection period of the storage ring to less than 1 minute. Simulations demonstrate expected performance, with a transmission efficiency about 90%, confirming its capability to meet the injection requirement of the SAPS storage ring. This design offers a stable and efficient solution for the SAPS.

Full Text

Preamble

Candidate Injector Design for the Southern Advanced Photon Source Based on Linac and Booster

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The Southern Advanced Photon Source (SAPS) is a diffraction-limited synchrotron light source currently under design that employs longitudinal injection as its primary injection scheme. This injection approach requires an injected beam with short bunch length and low emittance, while the preferred injector should offer high stability and low cost. Consequently, a booster synchrotron-based injector has been developed. The proposed injector includes a 250 MeV linac, a booster synchrotron that ramps beam energy to 3.5 GeV, and two beam transport lines to ensure efficient beam delivery and preservation of beam quality. The linac utilizes a thermionic high-voltage DC gun for reliable operation and features a bunching system with an advanced focusing system to preserve emittance. To meet SAPS injection requirements, a comprehensive booster design has been conducted. The booster synchrotron employs a three-fold lattice structure incorporating modified theoretical minimum emittance cells with a small momentum compaction factor and high RF voltage to achieve an emittance of 3.98 nm · rad and a bunch length of 4.8 mm. The injector has the potential to deliver high charge, reducing the storage ring injection period to less than one minute. Simulations demonstrate expected performance with a transmission efficiency of approximately 90%, confirming its capability to meet SAPS storage ring injection requirements. This design offers a stable and efficient solution for SAPS.

Keywords: Southern Advanced Photon Source, longitudinal injection, booster synchrotron, emittance, bunch length

Introduction

Diffraction-limited storage rings (DLSRs) represent a new generation of storage-ring-based light sources designed to deliver high-brightness synchrotron radiation by minimizing beam emittance to approach the diffraction limit of X-rays. MAX-IV [1, 2] pioneered this technology as the first diffraction-limited light source, and subsequently numerous DLSRs [3–15] have been launched worldwide. To achieve ultra-low beam emittance within a reasonable circumference, DLSR designs typically incorporate a multi-bend achromat (MBA) [16] lattice with a small dynamic aperture. Alternative injection schemes [17–26] with relaxed dynamic aperture requirements have been extensively explored, particularly novel on-axis injection approaches [19–26] that require a dynamic aperture only a few times larger than the injected beam size. One such on-axis method is swap-out injection [19], which has been implemented by several DLSRs [20–22]. Another option is longitudinal injection, where the bunch is injected on-axis transversely but with an energy and/or phase deviation relative to the synchronous particle. Longitudinal injection demands superior beam dynamics performance to accommodate the oscillations of the injected beam, including low emittance and very short bunch lengths.

The horizontal natural emittance of an electron beam in a ring can be expressed as [27]:

$$\epsilon = C_q \frac{F(\text{type})}{J_x N_b^3}$$

where $C_q = 3.83 \times 10^{-13}$ m, γ is the Lorentz factor with speed of light c, J_x is the horizontal damping partition number, and $F(\text{type})$ is a dimensionless quantity depending on the lattice type. For example, F is $1/(12\sqrt{15})$ for a theoretical minimum emittance (TME) unit cell. N_b denotes the number of bending magnets, and increasing N_b effectively decreases emittance; to a certain extent, increasing N_b is equivalent to enlarging the ring circumference. The root mean square (RMS) bunch length σ_L is given [28] as:

$$\sigma_L = \sqrt{\frac{2\pi heV\alpha_p}{E|\cos\phi_s|}}\sigma_E$$

where σ_E is the RMS energy spread, e is the electric charge, α_p is the momentum compaction factor, C is the ring circumference, h is the harmonic number, V is the cavity voltage, and ϕ_s is the synchronous phase. It is clear that increasing the voltage, reducing the circumference, and lowering α_p can decrease bunch length. Considering both bunch length and emittance, reducing α_p becomes the primary optimization option in lattice design.

The demand for a high-performance synchrotron light source is gradually increasing in southern China, leading to the proposal of the Southern Advanced Photon Source (SAPS) [29-31]. SAPS is a 3.5 GeV DLSR planned for construction near the China Spallation Neutron Source (CSNS) facility [32]. Together with CSNS, this new light source is expected to significantly enhance multidisciplinary scientific research in southern China. The current SAPS storage ring design spans 810 meters, provides an emittance of 26 pm • rad, and supports a beam current of 500 mA. To enhance light stability, SAPS employs longitudinal injection as its primary injection scheme [33].

For the injector system, several candidate options have been considered, including a full-energy linac injector [34] and a booster-based injector. The booster-based injector is preferred due to its utilization of highly stable and thoroughly validated conventional magnets and acceleration units, which offer superior stability and minimized instrumentation expenses. To further improve stability and operational efficiency, many boosters implement separate tunnels from the storage ring [35-52], a strategy also suggested for SAPS. [Figure 1: see original paper] presents key accelerator parameters worldwide for boosters with separate tunnels employed as injectors in light sources. These parameters include storage ring circumference, booster energy, emittance, and bunch length relative to booster circumference. Specifically, the upper left plot illustrates the circumference relationship, with most light sources exhibiting a ratio of approximately

3:1. The upper right plot summarizes booster acceleration energy, indicating an increase of roughly 2 GeV for every 100 meters of circumference. The emittance and bunch length relative to circumference are not clearly depicted in the lower plots, yet these highlight significant advantages in beam performance for the SAPS booster.

To fulfill beam quality and efficiency requirements for top-up operation modes of the storage ring, the booster-based injector should deliver electron bunches with high beam quality as summarized in Reference [53] and outlined in . With a bunch spacing of 6 ns in the storage ring, longitudinal injection must be precisely executed within this 6 ns period. To prevent disturbances to the circulating beam during injection and reduce kicker difficulty, the injection phase is positioned very close to the unstable phase of the RF bucket, which imposes significant constraints on longitudinal acceptance. Simulations demonstrate that high injection efficiency is achieved for bunch lengths under 5 mm. Moreover, significant energy oscillations during longitudinal injection, with peak energy deviations approaching 4%, reduce transverse acceptance. Consequently, the horizontal geometric emittance must be kept below 20 nm • rad. For standard longitudinal injection, the bunch charge needs to exceed 0.25 nC, identified as the normal-charge (Norm-Qc) mode. Once the storage ring is activated, the injection process from zero to full beam current is projected to take less than one minute, enhancing light source utilization. In this mode, each bucket in the ring is filled by a single injected bunch, demanding a bunch charge of 4.2 nC with an injection efficiency of 80%. This operational state is labeled the high-charge (high-Qc) mode.

As demonstrated by Eqs. (1) and (2), minimizing emittance and bunch length can be achieved by increasing ring circumference and reducing α_p. One approach to reduce α_p is the use of combined-function magnets, with optimization algorithms [54, 55] employed to design these lattices. To facilitate selection of optimal lattice structures, we conducted a comparative analysis. The main parameters of these lattices are summarized in , including a FODO structure with increased circumference, a modified TME structure, and a structure incorporating full combined-function magnets. To meet injection requirements, the FODO structure circumference must be increased to approximately 380 meters, significantly enlarging the accelerator and substantially increasing costs. Under equal circumference conditions, the key parameters of the TME structure are similar to those of the full combined-function magnet structure. However, during the design process, optimizing the nonlinear dynamics of full combined-function magnets proved particularly complicated and demanded higher tolerance for magnet errors. Considering both cost and operational reliability, the modified TME structure was ultimately selected.

[Figure 2: see original paper] displays the layout of the booster-based injector. The SAPS booster synchrotron-based injector consists of a 250 MeV linac, a booster synchrotron that accelerates beams to a full energy of 3.5 GeV for storage in the ring, and two transport lines. The paper is organized as follows:

Section II describes the preliminary linac design, outlining components and their functions. Section III elaborates on the booster synchrotron lattice design and beam parameters, closed orbit correction, longitudinal dynamics design, and high-intensity studies. Section IV presents the beam transport line design and booster injection/extraction, explaining their roles in beam delivery and manipulation. Section V introduces transmission efficiency simulations from the electron gun to the storage ring injection point. Section VI discusses the injector design for the longitudinal injection scheme. The concluding section summarizes findings and proposals, highlighting advancements in the SAPS project.

II. Linac Design

The 250 MeV linac functions as the pre-injector for the synchrotron light source, delivering electron bunches to the booster synchrotron. The pre-injector layout [56] is illustrated in [Figure 3: see original paper]. The system comprises three sections: a DC electron gun, a bunching section, and an accelerating section that includes four S-band accelerating cavities.

As a user facility, the linac should operate with high reliability, which is challenging when employing an RF photo gun equipped with a semiconductor cathode for high bunch charge. Therefore, a thermionic high-voltage DC gun is chosen, capable of providing the required bunch charge to the booster. The total capture efficiency is assumed to be 80%, so this DC gun must provide electron bunches with a charge of 6.5 nC. The software EGUN [57] is utilized for DC gun design. The full-width at half-maximum (FWHM) bunch length is 1.1 ns. For normal-charge mode, this gun can also provide bunches with low charge by adjusting the bias voltage.

The bunching system compresses the bunch into a single bunch, comprising two subharmonic cavities, a standing-wave S-band pre-buncher, a traveling-wave S-band buncher, and a standard S-band cavity. After passing through this bunching system, over 90% of electrons are confined within a time range of 10 ps, ensuring low energy spread acceleration in the subsequent linac. The entire system is encased in a solenoid focusing channel for transverse focusing and emittance preservation. Our design incorporates 23 solenoids, each with a maximum magnetic field of 0.1 T. The final traveling-wave cavity not only compresses the electron bunch but also provides beam acceleration. The bunch energy after this section is approximately 50 MeV.

The accelerating system comprises four traveling-wave S-band accelerating cavities to increase the bunch energy from 50 MeV to 250 MeV. Two adjacent cavities are grouped together and powered by a klystron. The microwave from the klystron is compressed using SLAC Energy Doubler (SLED) technology [58] to achieve high peak power. The average accelerating gradient of the linac can exceed 20 MV/m. Along the linac cavities, three quadrupole triplets are used to match and focus the beam. The wakefield in the S-band linac is also estimated, and BNS damping [59] is employed to mitigate its effects.

The linac operates in two distinct charge modes: standard-charge mode dedicated to longitudinal injection of the storage ring and a high-charge mode optimized for fast beam accumulation from zero to full current upon storage ring activation. The high-charge mode presents notable challenges to the linac, prompting a focused design approach. Alignment errors for all components are assumed to have RMS standard deviations of 0.1 mm and 0.1 mrad, while cavities and magnets are presumed to exhibit field errors of 0.1%. Following error assessment and correction, optimization and comparison tasks are performed using the ELEGANT [60] and ASTRA [61] codes, with main beam parameters detailed in . At the end, the beam energy reaches 250 MeV. The linac achieves a transmission efficiency exceeding 95%, accompanied by normalized emittances of approximately 60 mm · mrad in the transverse plane. A bunch charge of 5.2 nC is required for a booster with 80% transmission efficiency. The transition from high-charge mode to normal-charge mode can be seamlessly accomplished by adjusting the settings of the electron gun, solenoids, and cavities. In this context, the beam emittance and spread are diminished compared to high-charge mode, thereby enhancing injector performance. Nonetheless, a bunch charge of 0.4 nC is maintained with the same transmission efficiency as in high-charge mode.

III. Booster Synchrotron

A. Booster Lattice

The separate-tunnel booster features a three-fold structure, with each superperiod consisting of 12 modified TME cells and two matching cells. The layout and optical functions of one period are depicted in [Figure 4: see original paper]. The modified TME cell comprises a combined-function dipole magnet and a set of quadrupole magnets. The matching cell, composed of two dipole magnets and powered by five separate power supplies for the quadrupoles, provides flexibility in optimizing the lattice. The lattice includes three long (7.3 m) straight sections with zero dispersion for installation of RF cavities, as well as injection and extraction components. The main parameters of the booster are listed in . The circumference is shortened to 237 m, comprising 54 dipole magnets, 108 quadrupole magnets, and 51 sextupole magnets. The lattice achieves a sufficiently low horizontal emittance of 3.98 nm · rad at extraction, comparable to that of third-generation storage rings. The bunch length is attained through a small α_p of 1.75×10^{-3} and a high voltage of 7.5 MV. The design with low emittance and short bunch length necessitates strong focusing fields, leading to significantly large natural chromaticity. Furthermore, the peak value of the dispersion is below 0.2 meters. Consequently, a sextupole field to correct chromaticity is integrated into the combined-function dipoles to decrease the number of sextupole magnets.

Given the pre-injector beam parameters described in Section II, the transverse beam sizes are 1.7 mm × 1.5 mm, respectively. It is assumed that the magnet aperture should be no less than 10 times the beam sizes. In the booster, the maximum strength of dipole magnets is approximately 1 T, with a defocusing strength of 0.542 T/m and sextupole strength of 5.63 T/m^2. Three types of quadrupole magnets are utilized, with a maximum pole-face strength of 0.72 T. Additionally, one type of sextupole magnet is employed with a maximum pole-face strength of 0.6 T and a length of 0.15 meters.

In addition to the integrated sextupole component in the combined-function magnets, a family of sextupoles distributed in each TME cell is employed for chromaticity correction. Two additional families of sextupoles in the matching cell are utilized to minimize nonlinear driving terms. Independent power supplies for the sextupoles allow separate adjustments of horizontal and vertical chromaticity. Using a 6D code to track particles for 1024 turns, the dynamic aperture and corresponding frequency map are obtained. The sextupole strengths are optimized to achieve a sufficiently large dynamic aperture. The optimized dynamic aperture and frequency map are shown in [Figure 5: see original paper]. The results indicate that the dynamic aperture approximates 15 mm.

B. Tolerance and Correction

The ring is equipped with 54 BPMs for closed orbit correction, with one BPM positioned in each modified TME cell. It also has 73 dipole correctors, allocated as 38 for the horizontal plane and 35 for the vertical plane. The corrector fields are capable of tracking the energy ramp, ensuring orbit correction at all energy levels. Preliminary evaluations encompass magnet tolerances and the orbit correction system. outlines the assumed RMS tolerances for magnet alignment and fields. Another significant source of closed orbit distortion is the stray field from the extraction Lambertson magnet operating in DC mode, which significantly impacts the circulating beam, especially at low energy stages. A local bump has been designed to mitigate this distortion. Tolerances on magnet parameters are developed using analytical estimates, assuming Gaussian-type random errors in all magnets.

In orbit correction simulations, 1000 sets of random seeds are generated. With these BPMs and correctors, the closed orbit distortion due to errors listed in can be effectively corrected. The BPM-corrector configuration ensures that the orbit exhibits a maximum deviation of 1.5 mm in each plane after correction, as shown in [Figure 6: see original paper], with average RMS values of 0.23 mm and 0.2 mm in the horizontal and vertical planes, respectively. This requires a maximum corrector strength of 0.5 mrad, simplifying magnet design and fabrication. Furthermore, based on orbit correction, an analysis is conducted to evaluate the impact of magnet alignment errors and field errors on the dynamic aperture. Considering the errors specified in , the dynamic aperture is reduced to 12 mm, yet it still meets the dynamic aperture requirements for both charge modes.

C. Longitudinal Beam Dynamics

The ramp cycle consists of a 60 ms flat bottom for accumulating the injected beam at the beginning, a ramping curve for acceleration, an equally long flat top for extracting the accelerated beam, and a ramping-down period. Reference [62] discusses the impact of various ramping curves on emittance. Given the 60 ms flat top and enhanced ramping accuracy, a comparable sinusoidal curve of energy $E(t)$ is utilized over a duration of 220 ms:

$$E(t) = 1.875 + 1.625\sin(2\pi f t)$$

with $f \approx 2.2727$ Hz and ramping time t. The ramping curve and beam evolution in the booster are depicted in [Figure 7: see original paper]. The beam energy increases from 250 MeV to 3.5 GeV in 220 ms. The RF voltage is set to 2 MV at injection and 7.5 MV at extraction. The synchrotron tune shifts from 0.026 at injection to 0.015 at extraction, while the bucket height reduces from 7% to 4%. The evolution of beam energy spread and emittance with energy ramping is detailed in Reference [63] as:

$$\frac{dA_i}{dt} = -\frac{A_i}{\tau_i(E)} + C_q \frac{\dot{E}}{E} G_i$$

with $i = 1$ and 2. For $i = 1$, A_1 denotes the energy spread, J_1 is the longitudinal damping partition, and $G_1 = I_3/I_2$ with synchrotron radiation integrals I_2 and I_3. For $i = 2$, A_2 represents horizontal emittance ϵ_x, J_2 is the horizontal damping partition J_x, and $G_2 = I_5/I_2$ with synchrotron radiation integral I_5. $\dot{E}$ is the energy slope at energy E with relativistic energy factor γ. P_γ is the synchrotron radiation power. When the energy exceeds 2.5 GeV, the emittance and energy spread attain equilibrium as a result of radiation damping and quantum excitation.

Additionally, the induced eddy current in the dipole vacuum chamber produces an extra sextupole field. The induced sextupole strength during ramping [64, 65] is calculated as:

$$B_2 = \frac{2F\mu_0\sigma}{\pi h g}\frac{dB}{dt}$$

where σ is the conductivity, h and g are the thickness and height of the vacuum chamber, respectively. F is the chamber form factor and μ_0 is the magnetic permeability of vacuum. For the specified lattice parameters, the estimated maximum sextupole field is 0.3 T/m^3 at a repetition rate of 2 Hz. The corresponding chromaticity values are approximately 1.7 for the horizontal plane and -1.3 for the vertical plane, which are significantly smaller than the natural chromaticity and can be easily compensated by ramping up sextupoles.

D. Estimation of Beam Effects Due to High Intensity

SAPS is in the design phase, making development of an accurate impedance model challenging. However, key impedance-contributing components can be inferred from other existing accelerators. In this study, we construct a vertical impedance Z_v, as depicted on the left side of [Figure 8: see original paper], by scaling the impedance of the HEPS booster [66, 67] as:

$$Z_v = \frac{C_{\mathrm{HEPS}}}{C_{\mathrm{SAPS}}} Z_{\mathrm{HEPS}} + N_c Z_{\mathrm{HOM}}$$

where C_{HEPS} is the circumference of the HEPS booster [51] and the number of cavities $N_c = 5$. A 5-cell copper cavity will be employed, serving as the source of higher-order modes (HOM, Z_{HOM}) observed in the impedance spectrum. Z_{HEPS} refers to the HEPS booster impedance excluding cavity impedance.

Instabilities commonly observed in other accelerators [68, 69] are estimated for the booster. For the high-charge mode, the beam current in the booster is approximately 20 mA. The growth time $1/\tau$ of transverse coupled-bunch instability (TCBI), driven by HOMs, is expressed [70] as:

$$\frac{1}{\tau} = \frac{f_{\mathrm{rev}} I_b \beta Z_{\mathrm{HOM}}}{2E/e}$$

where I_b is the average beam current with revolution frequency f_{rev}, and β is the beta function at the cavity. The growth time in the vertical plane is calculated to be 0.78 ms at injection and 11 ms at extraction. These results indicate that the TCBI growth time at extraction energy exceeds the damping time of 6.3 ms, thereby suppressing the instability. Conversely, the beam remains unstable at injection due to the excessively long damping time. Consequently, a transverse feedback system with a damping time of 0.5 ms is proposed.

Single-bunch effects are simulated utilizing the ELEGANT code [60] for the bare lattice, with threshold charges depicted on the right side of [Figure 8: see original paper]. The head-tail instability is observed at high bunch charges in the simulation. As head-tail effects emerge, both the oscillation amplitude of beam position and the vertical emittance increase. Nevertheless, the results show that the instability threshold charge is around 15 nC, substantially higher than the required charge of 4.2 nC for high-charge mode. Furthermore, a longitudinal impedance model is also developed to investigate the dependence of bunch length on bunch charge. The findings reveal that bunch length increases significantly due to microwave instability when the charge exceeds 20 nC. Consequently, bunch lengthening is expected to be negligible in both normal-charge and high-charge modes.

IV. Beam Transport Lines and Booster Injection, Extraction

References [71-73] serve as the basis for design considerations in this section. The Linac-to-Booster Transport line (LBT) connects the linac to the booster. The transfer line must fulfill several functions: beam matching between the linac and booster, and providing space for beam diagnostic elements and momentum collimators. The high-charge mode is considered in the design. The transfer line consists of two doublet bend achromat (DBA) structures, ensuring a dispersion-free condition. It includes 3 dipoles and 12 quadrupoles, with all dipole magnet angles set at 200 mrad. Instrumentation elements are arranged along the 24.4 m transfer line. The maximum beta function is 35 m with maximum dispersions of 0.6 m. The horizontal collimator is positioned in the first DBA structure with a transverse aperture of 16 mm, effectively reducing the energy spread to the required level. The RMS energy spread after collimation is 0.36%. Error studies show that beam emittance does not significantly increase along the transfer line, and beam loss is mainly confined to the collimation section.

The booster injection system is situated in one of the two remaining dispersion-free straight sections and comprises a DC Lambertson magnet and a kicker. It utilizes single-turn on-axis injection, enabling injection of one bunch into the booster RF buckets. The Lambertson has a bend angle of 200 mrad in the horizontal plane, while the kicker has a bend angle of 6.5 mrad in the vertical plane.

The booster extraction system is located in the last dispersion-free straight section and comprises four slow orbit bumpers, a Lambertson magnet, and a kicker. The slow bumpers incrementally shift the orbit of the circulating bunch train toward the extraction Lambertson over several hundred turns. Following this, the extraction kicker directs one bunch into the extraction Lambertson at a vertical angle of zero. The kicker strength is 1.2 mrad, while the Lambertson kick angle is set at 100 mrad. Two of the four bump magnets are positioned in the matching cell, with a maximum bumper strength of 1.3 mrad. Simulations confirm the design, achieving 100% extraction efficiency. Additionally, the beam carrying a charge of 5 nC is tracked from injection to extraction in the booster, with primary results shown in [Figure 9: see original paper]. The injected beam quickly reaches equilibrium after injection in the booster. During the injection plateau phase, these parameters show minimal change, while in the acceleration phase they gradually stabilize and reach equilibrium values. This outcome indicates high beam performance throughout the booster cycle.

The Booster-to-Ring Transport line (BRT) is designed to efficiently convey the booster beam into the storage ring. Due to the low vertical emittance, the beam is vertically injected into the ring to minimize kick intensity in the storage ring. The BRT consists of 12 dipoles and 19 quadrupoles, extending over a length of 60 m. This transport line is functionally divided into three segments: the extraction matching section, the dispersion-free section, and the injection matching section. The dispersion-free section is allocated for installation of beam diagnostic elements. The magnet aperture is less than 30 mm. The beam transmission efficiency in the BRT is approximately 99%.

V. Transmission Efficiency Simulation

After completing the physical design of the injector, we studied the overall transmission efficiency. Transmission efficiency is defined as the ratio of charge captured by the storage ring to charge output from the electron gun. The start-to-end simulation is systematically executed to ensure that input parameters at each accelerator stage precisely match the output parameters of the preceding stage, facilitating a seamless acceleration and transmission process. The simulation rigorously tracks the beam from its generation at the electron gun through the linac, the LBT, injection, acceleration, and extraction in the booster, and the BRT, ultimately reaching the injection point in the storage ring. Realistic error margins expected at each accelerator stage are incorporated into the simulation. To evaluate overall performance, we generate 100 random seeds and perform a comprehensive statistical analysis of transmission efficiency and charge accumulated in the storage ring.

First, the high-charge mode is simulated. The results demonstrate exceptional efficiency, with an average transmission efficiency approaching 90%, and most beam loss occurring at the collimator in the LBT. Furthermore, across all simulation scenarios, the accumulated charge in the storage ring exceeded the required charge of 3.33 nC. This indicates that our injector design meets the criteria for efficient injection even when realistic operational errors are considered. To further validate the robustness of the injector design, equivalent simulation studies are performed for the normal-charge mode. Encouragingly, in this mode the transmission efficiency exceeds 90% in every case, providing additional evidence of the design’ s efficiency and reliability.

VI. Discussion

Synchrotron radiation light sources are undergoing rapid development globally. Selecting an injector with high stability, high beam quality, robustness, and cost-effectiveness is crucial to advancing these facilities. Presently, synchrotron radiation light sources are categorized as high, medium, and low-energy sources based on beam energy. High-energy light sources, exemplified by HEPS [14], operate at energies exceeding 6 GeV and favor booster-based injector schemes for efficient cost management. Low-energy light sources, with energies below 2.5 GeV, can accommodate a full-energy linac injector due to lower energy requirements, as illustrated by HALF [15]. Medium-energy light sources fall between these extremes and necessitate thorough consideration of various injector options. For instance, SAPS has assessed multiple injector schemes, including full-energy linac, booster-based injection, and innovative injectors, to align with technical requirements, costs, and future expansion applications. Despite the availability of innovative injector schemes and technologies such as laser plasma accelerators, these alternatives often introduce heightened operational risks. Recent studies have shown that booster-based injectors offer significant advantages over other injector types.

The longitudinal injection design of SAPS imposes stringent requirements on injector beam quality, particularly concerning bunch length and beam emittance. Achieving the desired bunch length and emittance while keeping the booster size reasonable presents a critical challenge. One strategy involves increasing the RF voltage. To attain the required beam quality, the voltage must be increased by an order of magnitude, necessitating sufficient space for RF cavity installation. Another method entails compressing α_p, which requires strong focusing fields, reducing the dynamic aperture and tightening magnet error tolerances. These challenges escalate not only the cost of the injector but also construction risks, potentially undermining the advantages of a booster-based injector. Balancing these factors, a hybrid approach has been adopted, combining α_p compression and voltage augmentation to preserve the benefits of the booster-based injector. The booster injector offers a promising solution for the longitudinal injection scheme of DLSR storage rings. Considering limitations such as simulation assumptions and the incorporation of more practical parameters in subsequent optimizations, future work will focus on optimizing design parameters, enhancing system stability, and preparing for actual construction stages. Nevertheless, successful beam commissioning from the HEPS injector [74, 75] offers substantial encouragement for ongoing success.

VII. Summary

A beam with short bunch length and low emittance is vital for SAPS storage ring injection. This paper presents a detailed overview of the physical design of a booster-based injector engineered to meet these requirements. The injector system comprises a linac, a booster synchrotron, and two beam transport lines. The booster synchrotron accelerates electron beams from 250 MeV to 3.5 GeV at a repetition rate of 2 Hz. The booster synchrotron lattice consists of 54 dipole magnets, 108 quadrupole magnets, and 51 sextupole magnets. The required beam parameters for SAPS injection are achieved by employing a modified TME structure with a small momentum compaction factor and high RF voltage. The resulting beam emittance is 3.98 nm • rad with a bunch length of 4.8 mm. Simulation studies of beam transmission efficiency indicate an overall efficiency of about 90%. Detailed analysis of beam collective effects, based on the current impedance model, shows that the charge stored in the injector significantly exceeds SAPS injection requirements. These findings confirm that the injector meets the injection requirements of the SAPS storage ring. The theoretical and simulation studies of the injector design demonstrate outstanding performance.

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