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# EFFICIENCY AND ERROR ANALYSIS OF THE HALS INJECTION SCHEME*

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*Abstract*

Hefei Advanced Light Source (HALS) is a newly designed diffraction-limited storage ring. The latest version of HALS has a 7BA lattice. One of the most important parts about HALS design is its injection system. Since conventional injection scheme is not suitable for DLSRs, many new injection schemes are proposed, including longitudinal injection scheme. In this paper, we investigate the feasibility of longitudinal injection scheme for HALS. In order to evaluate the injection performance, various errors have been considered. A series of tracking simulations are carried out and injection efficiency is obtained under different error levels.

## INTRODUCTION

Hefei Advanced Light Source (HALS) that is proposed by NSRL is a new VUV and soft-X ray diffraction-limited storage ring-based light source. A project to build test facility of this new light source has been approved and funded in 2017. After repeated design studies, a 7BA lattice is presented for HALS [1, 2]. Among many key subsystems, the injection system of HALS is a very important one. It's quite difficult for DLSRs to adopt conventional local bump method for injection, because the machine aperture and dynamic aperture of DLSR are quite small. HALS provides a very low natural emittance of 23.2 pm·rad, and its machine aperture and dynamic aperture are about 11 mm and 2 mm respectively. Many new injection options, such as swap-out injection, multipole kicker injection and longitudinal injection, are explored and investigated. An additional accumulator ring is necessary to extract weakened bunches in swap-out injection, and this would increase cost [3]. Multipole kicker injection has been experimentally examined by KEK and shows good performance, but it needs larger dynamic aperture [4]. Longitudinal injection is an on-axis injection scheme which is effective and much simpler [5]. But requirements for kickers are restrictive and higher energy acceptance is necessary for longitudinal injection.

Considering the construction cost and technical difficulties, longitudinal injection scheme is a preferred option for HALS. The latest 7BA lattice has higher momentum acceptance, which is good for longitudinal injection. And to improve injection efficiency, HALS chooses a full energy Linac with a beam emittance of sub-nanometer as an injector. 6D accelerator program ELEGANT is applied for particle tracking [6].

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## LONGITUDINAL INJECTION

In the longitudinal injection scheme, the injected bunches and circulating bunches have different phases. With a time and momentum offset, an injecting bunch can be kicked transversely on-axis between two circulating bunches by short-pulse dipole kickers. To keep circulating bunches undisturbed, the pulse of kicker field has to be shorter than the bunch spacing. This increases technical difficulties for kickers. When the RF frequency is 100 MHz, the pulse length of kicker shall be no more than 10 ns.

In the latest version of HALS, longitudinal gradient and anti-bend dipoles are used in the lattice design. And the beam energy changes from 2.0 GeV to 2.4 GeV. It has higher momentum acceptance. The optical function and magnet layout of one cell of HALS storage ring is shown in Fig. 1. The dipole, quadrupole and sextupole magnets in the figure are indicated in red, black and green respectively. The magenta indicates anti-bend dipole.

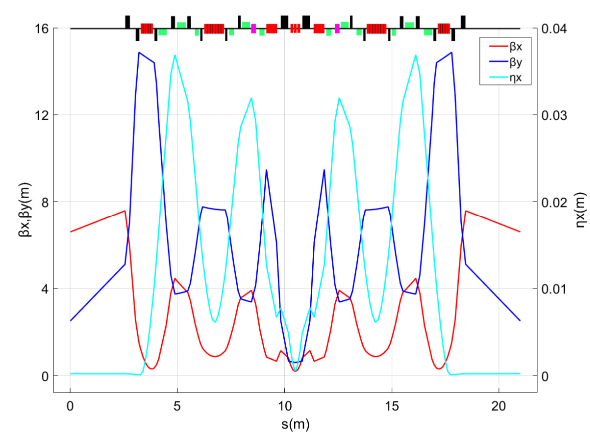


Figure 1: Optical function and magnet layout of the HALS MBA lattice.

The synchronous phase $\varphi_s$ and momentum acceptance $\delta_{acc}$ are given by:

$$\varphi_s = \pi - \arcsin(\frac{U_0}{eV_0}) \quad (1)$$

$$\delta_{acc} = \sqrt{-\frac{2eV_0}{\pi E_0 h\alpha}\left[\cos(\varphi_s) + \left(\varphi_s - \frac{\pi}{2}\right)\sin(\varphi_s)\right]} \quad (2)$$

Where $U_0$ is energy loss per turn due to synchrotron radiation, $V_0$ is RF voltage, h is harmonic number, $\alpha$ is momentum compaction factor. The detailed parameters about HALS are listed in Table 1. The momentum compaction factor of HALS is 3.5x10$^{-5}$, it's quite small. According to Eq. (2), we know that the bucket height is 5.15%, when RF voltage is set as 350KeV. Figure 2

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shows the longitudinal phase space of HALS. The red lines indicate the stable bucket, the grey lines indicate trajectories outside the acceptance, the cyan lines show the particle trajectories that have been tracked for 65000 turns in the longitudinal phase space with synchrotron radiation loss.

Table 1: Main Parameters for Longitudinal Injection

| Parameter | Value |
|---|---|
| Beam energy [GeV] | 2.4 |
| Circumference [m] | 672 |
| Natural emittance [pm] | 23.2 |
| Radiation loss [keV/turn] | 217.6 |
| Harmonic number | 224 |
| RF frequency [MHz] | 100 |
| RF voltage [kV] | 350 |
| Momentum compaction factor | $3.5\text{x}10^{-5}$ |
| Tune, $\nu_x/\nu_y$ | 78.33/29.30 |
| Damping time, $\tau_x/\tau_y/\tau_s$ [ms] | 32.7/49.4/33.2 |
| Synchronous phase [deg] | 141.56 |

For a particle injected at -5ns, its upper limit and lower limit of momentum offset are 7.94% and 7.03% respectively. Particles with higher or lower momentum offset would be lost. The blue point at left is the unstable point, and the right one stable point. According to our simulation, most of the injected particles within energy acceptance would be lost nearby unstable point. In about 4 to 5 times of longitudinal damping time, particles in the stable bucket would merge to the circulating bunches by synchrotron damping. The higher energy the particle has, the shorter time it needs. The stable bucket can be enlarged if a higher harmonic cavity is added in the storage ring. We have not included a higher harmonic cavity in our simulation in this paper.

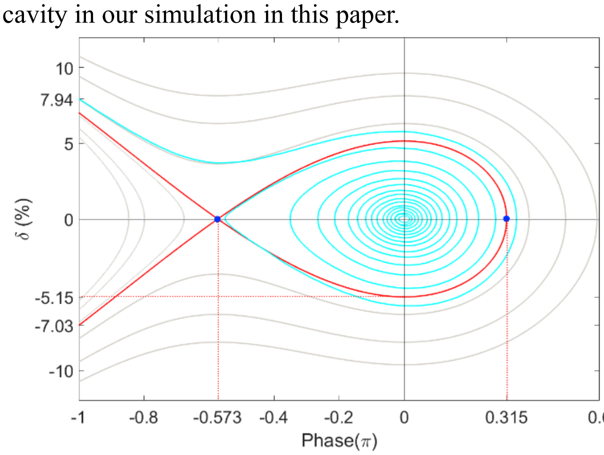


Figure 2: Longitudinal phase space.

## SIMULATION STUDIES

In a realistic machine, various errors may occur. To evaluate the performance of longitudinal injection scheme, we have two kinds of errors in our simulation studies: mismatch error and injected beam trajectory error. The mismatch error include transverse optical function mismatch, longitudinal mismatch and energy mismatch. We use emittance, energy spread, momentum offset and bunch length to measure these errors. The injector of HALS is a full energy Linac. The design requirements for injected bunches are: a normalized emittance of 2mm·mrad, the bunch length about 10 ps (FWHM) and energy spread less than 0.1%. In our simulation, the injected bunch is assumed to have 20 ps rms bunch length and an emittance of 1.0 nm·rad. Momentum offset and energy spread have a great impact on capture efficiency of injected beam, as shown in Fig. 3. When energy spread is about 0.05% and momentum offset is 7.2%~7.7%, the injection system shows better performance.

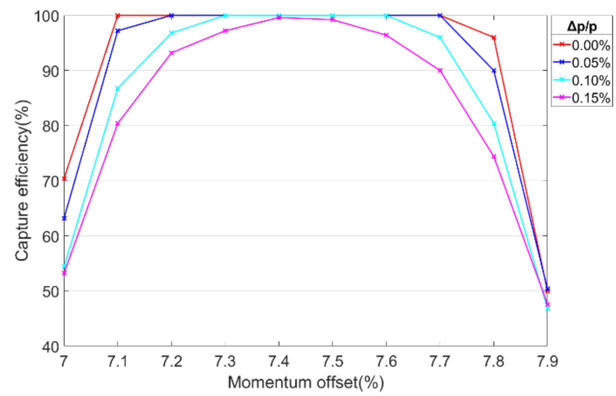


Figure 3: Capture efficiency vs. momentum offset at different energy spread.

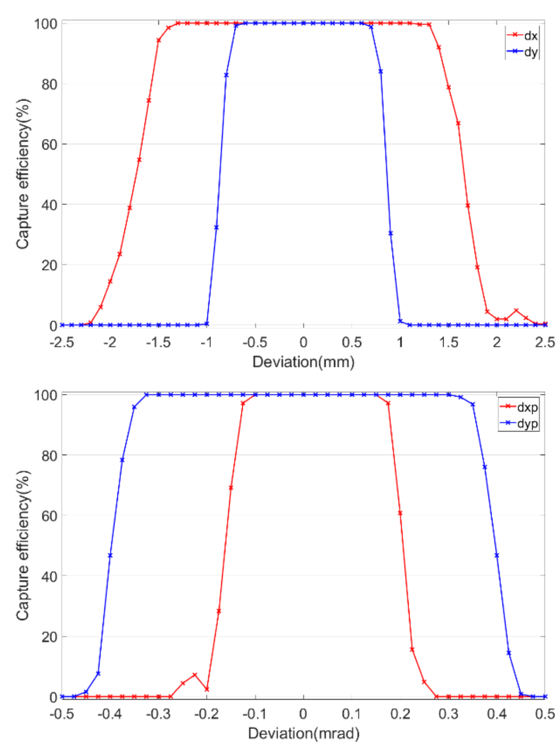


Figure 4: The capture efficiency under four types of injection deviation.

Injected beam trajectory error includes trajectory error at injection point, pulse to pulse jitter and bending angle errors of septum and strip-line kickers. These errors are

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equivalent to deviation of (*x, x', y, y', t*) of injected bunches. We can see in Fig. 4. how capture efficiency changes over the deviation of *x, x', y* and *y'*. The momentum offset and energy spread are 7.5% and 0.1% respectively. For the convenience of simulation, we assume the four types of deviation have no correlations with each other. The HALS lattice has higher requirement for the deviation of *y* and *x'*. Table 2 summarizes the ranges of deviation when the capture efficiency is more than 80%.

Table 2: Deviation Ranges of the Injected Beam

| Deviation variable | Range of >80% efficiency |
|---|---|
| $\Delta x$ [mm] | [-1.57,1.49] |
| $\Delta x'$ [mrad] | [-0.14,0.19] |
| $\Delta y$ [mm] | [-0.81,0.81] |
| $\Delta y'$ [mrad] | [-0.37,0.37] |

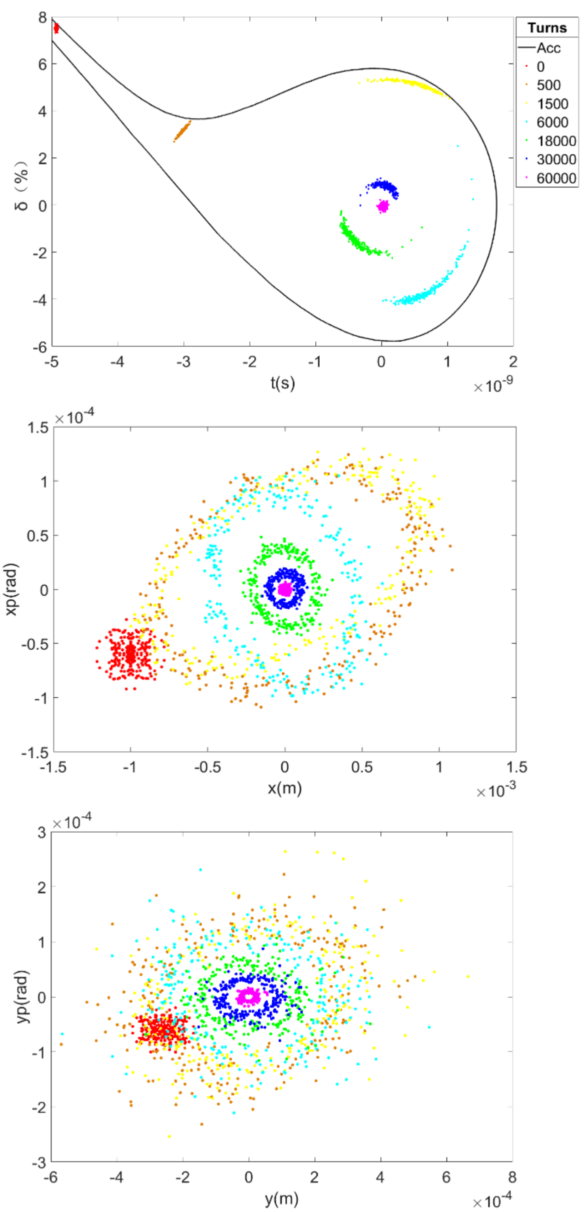


Figure 5: Particle distributions in the longitudinal and transverse planes

To investigate the feasibility of longitudinal injection scheme for HALS, we have taken many errors into consideration. A bunch of 250 particles have been tracked using Elegant. Detailed errors in our simulation are listed in Table 3. The results are shown in Fig. 5. The top picture is particles distributions in longitudinal plane, the middle and bottom one show the particles in transverse phase space. After 60000 turns (4.11 times of damping time in the horizontal plane, 2.72 times in the vertical plane, and 4.04 times in the longitudinal plane), the injected bunch is successfully damped, and no particle is lost.

Table 3: Errors used in the Simulation

| Parameter | Value | Sources |
|---|---|---|
| $\varepsilon_x/\varepsilon_y$ [nm·rad] | 1.0/0.6 | Transverse mismatch |
| $\Delta\delta$ | 7.5% | Linac energy |
| $\Delta t$ [ps] | 70 | Relative rf phase |
| $\Delta p/p$ | 0.66% | Energy mismatch |
| $\Delta x/\Delta y$ [mm] | -1.1/-0.26 | Jitter, trajectory |
| $\Delta x'/\Delta y'$[m·rad] | -0.06/-0.06 | Jitter, trajectory |

## CONCLUSION

We investigate the longitudinal injection scheme for the 7BA HALS. With a time and energy offset, the bunch from full energy Linac can be injected between two successive circulating bunches. Through synchrotron damping, the injected bunch is finally merged to circulating bunch. In our simulations, we have analysed many types of errors that could happen in realistic injection progress. Longitudinal injection scheme shows good performance in theory for HALS. But more experiments need to be done to verify the feasibility of this injection scheme.

## REFERENCES

[1] Zheng-He Bai, *et al.,* "Initial Lattice Design for Hefei Advanced Light Source: A VUV and Soft X-ray Diffraction-limited Storage Ring.", presented at IPAC'16, Busan, Korea, May 2016, paper WEPOW027, pp. 2889-2891

[2] Zheng-He Bai, *et al.,* "Design study for the first version of the HALS lattice", presented at IAPC'17, Copenhagen, Denmark, May 2017, paper WEPAB060, pp. 2713–2715.

[3] Xiao, Aimin, and Vadim Sajaev. "Simulation study of injection performance for the Advanced Photon Source upgrade." presented at IPAC'15, Richmond, VA, USA, May 2015, paper TUPJE075, pp. 1816-1818

[4] H. Takaki et al., "Beam injection with a pulsed sextupole magnet in an electron storage ring", Phys. Rev. ST Accel. Beams, 13, 020705 (2010)

[5] M. Aiba et al., "Longitudinal injection scheme using short pulse kicker for small aperture electron storage rings", Phys. Rev. ST Accel. Beams, 18, 020701 (2015).

[6] M. Borland, "ELEGANT: a flexible SDDS-compliant code for accelerator simulation", APS Tech. Report LS-287, Argonne, April 2000.