ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM082

PRELIMINARY ELECTRON INJECTOR DESIGN FOR A STEADY-STATE MICROBUNCHING LIGHT SOURCE*

X. Zhang†, Z. Pan, P.-W. Huang, Y. Jiang, Y. Jia, L. Chen, J. Shi, W. Huang, R. Li‡, C. Tang
Department of Engineering Physics, Tsinghua University, 100084 Beijing, China
Key Laboratory of Particle and Radiation Imaging of Ministry of Education,
Tsinghua University, 100084 Beijing, China

Abstract

The Steady-State Microbunching (SSMB) mechanism [1], which combines the benefits of high repetition rate of a storage ring and coherent radiation, has the potential to produce high average power short wavelength light [2]. In order to generate kilowatt level radiation, the electron injector should have the ability to provide a 1 A average current, 100 ns long DC beam, with the requirements of small emittance (<1 mm· mrad), and very small energy spread (<5×10^{-4}) for the SSMB storage ring. This paper presents an overview of the physical design of the electron gun, linac, and stretching ring components of the injector, as well as the beam loading compensation methods employed in the electron gun and linac.

INTRODUCTION

The conceptual design of the SSMB high average power light source is shown in the Fig. 1 [3], where the injector is mainly composed of a 400 MeV linac and a stretching ring. The electron gun used in the SSMB mechanism is an ultra-high vacuum S-band electron gun with a resonant frequency of 2856 MHz [4]. The operation mode of the electron gun and linac is shown in Fig. 2. The electron gun and S-band linac will accelerate a train of bunches to 400 MeV, which will then be converted into a DC beam by the stretching ring. Due to the high current and long length of bunch train, beam loading and multi-bunch beam breakup in linac is critical. Beam loading compensation by using rf phase to amplitude modulation method and ΔT method will be introduced. Additionally, a new method of beam loading compensation will be discussed.

PHYSICAL DESIGN OF INJECTOR

Electron Gun

The electron gun is required to accelerate 300 electron bunches in a macropulse with an interval of 350 ps (corresponding to 2856 MHz), and each bunch charge needs to be 350 pC to maintain an average beam current of 1A. The ΔT method is used in beam loading compensation in electron gun [5]. Beam-induced voltage V_b [6] by a point charge q

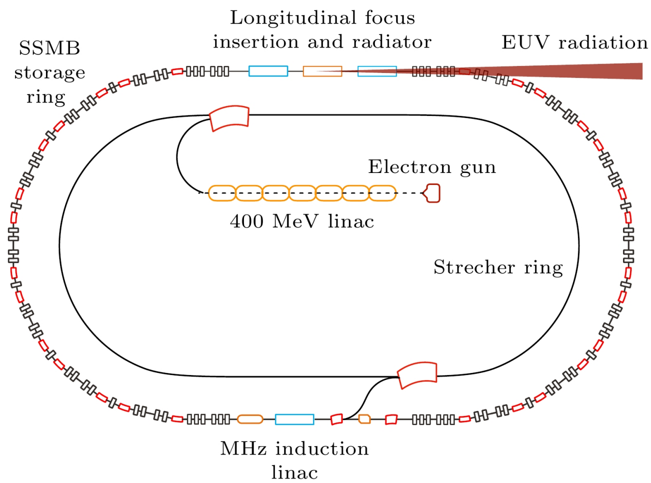

Figure 1: Conceptual design of the SSMB high average power light source

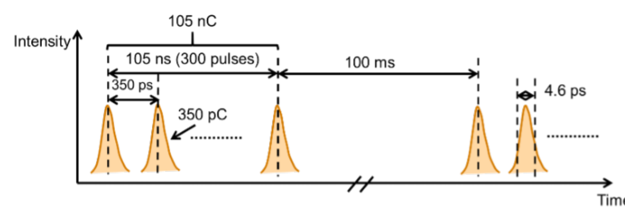

Figure 2: Operation mode of electron gun and linac

after crossing a structure with shunt impedance R_s is

$$V_{b0} = -2kq = -\frac{\omega R_s}{2Q_0}q \tag{1}$$

In an electron gun with filling time of t_f, for an electron bunch train composed of a series of bunches spaced at t_b (t_b is an integer multiple of the microwave period), the loading voltage at time t is given by:

$$\begin{aligned} V_b(t) &= \frac{1}{2}V_{b0} + (V_{b0}e^{-\frac{t_b}{t_f}} + \cdots + V_{b0}e^{-(n-1)\frac{t_b}{t_f}}) \\ &= V_{b0}\frac{1-e^{-(t-t_1+t_b)/t_f}}{1-e^{-\frac{t_b}{t_f}}} - \frac{1}{2}V_{b0} \end{aligned} \tag{2}$$

where t_1 is the injection time of the first bunch. The accelerating voltage of a microwave electron gun at time t is given by:

$$V(t) = \frac{2\sqrt{\beta P R_0 T^2}}{1+\beta}(1-e^{-t/t_f}) \tag{3}$$

* Work supported by the National Key Research and Development Program of China No.2022YFA1603400 and the Tsinghua University Initiative Scientific Research Program No. 20197050028, 20191081195.
† xy-zhang20@mails.tsinghua.edu.cn
‡ lirk@tsinghua.edu.cn

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM082

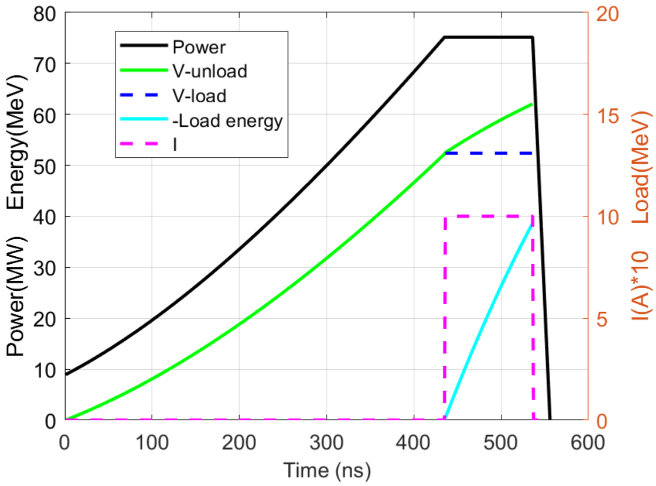

Figure 3: The time dependence of the input rf power (black), beam current (pink), and the corresponding unloaded (green), loaded (blue), and beam (light blue) voltages are shown.

where β is the cavity coupling coefficient and P is input power.

The net energy gain of each electron bunch within the macropulse can be identical if the difference between Eq. (2) and Eq. (3) is a constant.

Linac

The linac is a traditional normal conducting S-band accelerator. The conventional approach for beam loading compensation is the phase to amplitude modulation method [7], which gradually increase the rf feed power to counter-balance the beam loading induced field decrease. By performing theoretical calculations [8], we obtained the power waveform required at an average current intensity of 1 A, as shown in Fig. 3.

We conducted an experiment in which the ramped power was generated by combining the power of two klystrons through a 3 dB coupler. The output of the coupler depends on the phase of the input microwave, allowing us to achieve the desired waveform by controlling the output microwave phase of both klystrons. Fig. 4 compares the power waveform obtained experimentally and theoretically. It is observed that the rising edge and flat region of the waveform obtained experimentally match well with the theoretical waveform. However, the presence of a falling time causes a difference between the experimental and theoretical waveform. Nonetheless, the falling edge does not affect the compensation for the beam loading effect. The experimental waveform was used to calculate the difference in the central energy of bunches, with the best result achieved being 6×10^{-4}.

Furthermore, we proposed a new method of beam loading compensation. Fig. 5 demonstrates the principle of using a single chicane to control central energy difference of electron bunches.

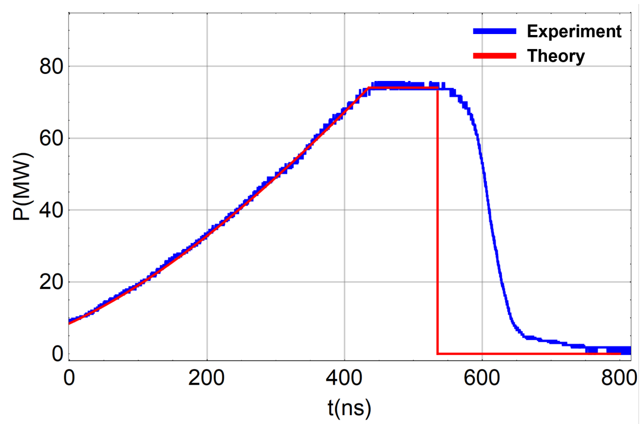

Figure 4: Experiment waveform and theoretical waveform

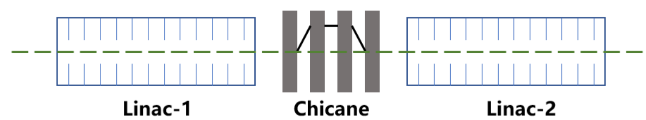

Figure 5: Layout of single-chicane scheme

Assuming the uniformly spaced bunches with equal energy in the bunch train before entering Linac-1, the first bunch will get the expected energy boost, but the bunches behind it will experience a lower energy boost due to beam loading. After Linac-1, the bunch train enters the chicane and the spacing between the bunches will be increase because of the energy chirp in the bunch train. When the stretched bunch train enters Linac-2, the tailing bunches witness higher acceleration phases than the heading bunches. By controlling the acceleration phase, different bunches get different energy boosts to compensate the beam loading. Using one single chicane, only the first-order bunch central energy difference can be compensated. More chicanes can compensate high-order inter-bunch average energy difference and intra-bunch energy spread.

We used the genetic algorithm to find the optimal layout of accelerating tubes and chicanes that minimizes the energy spread of the bunch train. The optimal beamline is shown in Fig. 6. We found that T363, T364, T463, T464 in second-order transfer matrix of chicane are large, additionally, the energy spread of the bunch train was found to be significant due to beam loading, which means that the contribution from energy spread, transverse size, and transverse divergence to emittance growth is considerable. Quadrupoles were cautiously positioned and adjusted to minimize the emittance growth during beam transport. Finally, 8 triplets were used to control the growth of emittance, and the final emittance met the requirements for injection.

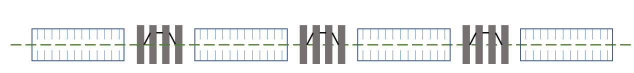

Figure 6: Layout of energy spread compensation beamline

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM082

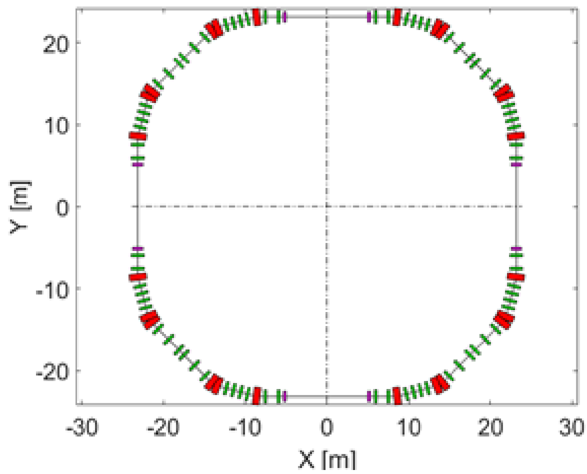

Figure 7: Stretching ring lattice

Stretching Ring

The stretching ring is an integral component of the injector. The bunch stretching process utilizes the natural momentum compaction effect of the storage ring to elongate each bunch within the 100 ns macropulse. Specifically, the longitudinal length of a bunch of electrons with a certain energy spread after running one lap in the storage ring will be elongated by $\Delta Z = \alpha\delta$, where α is the momentum compaction factor of the storage ring, δ is the energy spread of the bunch, and ΔZ is the longitudinal elongation per lap. Our designed stretching ring possesses a large momentum compaction factor for accomplishing this function. After injecting a bunch train with a certain energy spread into the stretching ring and running about 300 turns, the bunch train will evolve into a DC beam with a longitudinally uniform distribution.

Fig. 7 illustrates the lattice layout, where the dipole magnet is represented in red, the quadrupole magnet in green, and the solid black line indicates the straight sections. The parameters of stretching ring are summarized in Table 1. The optical functions in one super-period structure can be found in Fig. 8. In this ring, sextupoles were not utilized for chromaticity correction as circulating turns is small.

Table 1: Parameters of the stretching ring

Parameter	Value	Unit
circumference	141.24	mm
Beam energy	400	MeV
Tunes (x/y)	7.56 / 4.25	/
Natural chromaticity	-20.76 / -11.43	/
Momentum compaction factor	1.05×10^{-2}	/
Energy loss per turn	0.74	keV

START-TO-END SIMULATION RESULTS

We performed a start-to-end simulation for the injector. ASTRA [9] was utilized for simulations for the low-energy section, from the electron gun to the exit of the first accelerating tube. We optimized this section to minimize energy spread and emittance by employing a genetic algorithm. Elegant [10] was utilized for simulation from the first acceleration tube to the stretching ring exit. Fig. 9 illustrates the longitudinal phase space and current distribution of the bunch train after the stretching ring. The central energy of the bunch train is 400 MeV, and the RMS energy spread of the total bunch train is less than 3×10^{-4}. The transverse normalized emittance can be less than 0.7 mm·mrad.

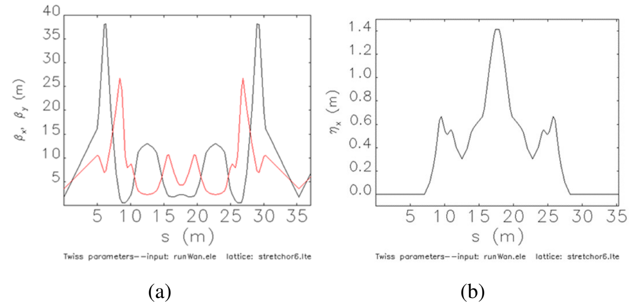

Figure 8: Optical functions in a super-period

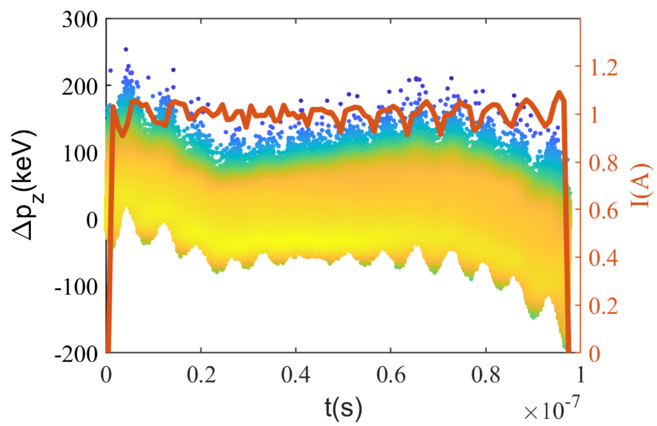

Figure 9: Longitudinal phase space and current distribution of DC beam at the exit of stretching ring (The color represents the density of electrons)

CONCLUSION

In summary, this paper presents the physical design of the injector for the SSMB high average power light source, and proposes a beam loading compensation technique for both the electron gun and linac. The results of the start-to-end simulation meet the requirements of injection into the main ring.

ACKNOWLEDGMENTS

Work supported by the National Key Research and Development Program of China No.2022YFA1603400 and the Tsinghua University Initiative Scientific Research Program No. 20197050028, 20191081195.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM082

REFERENCES

[1] D. Ratner and A. Chao, "Steady-state microbunching in a storage ring for generating coherent radiation", *Phys. Rev. Lett.*, vol. 105, no. 15, p. 154801, 2010. doi:10.1103/PhysRevLett.105.154801

[2] X. Deng *et al.*, "Experimental demonstration of the mechanism of steady-state microbunching", *Nature*, vol. 590, no. 7847, pp. 576–579, 2021. doi:10.1038/s41586-021-03203-0

[3] C. Tang and X. Deng, "Steady-state micro-bunching accelerator light source", *Acta Phys. Sin.*, vol. 71, no. (15), p. 152901, 2022. doi:10.7498/aps.71.20220486

[4] P. Huang *et al.*, "An ultrahigh-vacuum S-band photocathode radio-frequency electron gun", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1051, no. 1, p. 168251, 2023. doi:10.1016/j.nima.2023.168251

[5] A. Deshpande *et al.*, "Experimental results of an rf gun and the generation of a multibunch beam", *Phys. Rev. ST Accel. Beams*, vol. 14, no. 6, p. 063501, 2011. doi:10.1103/PhysRevSTAB.14.063501

[6] P. Wilson and J. Griffin, "High energy electron linacs; application to storage ring RF systems and linear colliders", in *AIP Conference Proceedings*, Batavia, IL, USA, July 1982, pp. 450–555. doi:10.1063/1.33620

[7] M. Satoh, *et al.*, "Initial-beam-loading compensation system for high-intensity electron linacs", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 538, no. 1, pp. 116–126, 2005. doi:10.1016/j.nima.2004.08.124

[8] A. Lunin, V. Yakovlev, and A. Grudiev, "Analytical solutions for transient and steady state beam loading in arbitrary traveling wave accelerating structures", *Phys. Rev. ST Accel. Beams*, vol. 14, no. 5, p. 052001, 2011. doi:10.1103/PhysRevSTAB.14.052001

[9] K. Floettmann, "A Space Charge Tracking Algorithm (ASTRA)". https://www.desy.de/~mpyflo/

[10] M. Borland, "elegant: A flexible SDDS-compliant code for accelerator simulation", *Advanced Photon Source LS-287*, September 2000. doi:10.2172/761286