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Abstract

Abstract High-brightness electron beams are required to drive LINAC-based free-electron lasers (FELs) and storage-ring-based synchrotron radiation light sources. The bunch charge and RMS bunch length at the exit of the LINAC play a crucial role in the peak current; the minimum transverse emittance is mainly determined by the injector of the LINAC. Thus, a photoinjector with a high bunch charge and low emittance that can simultaneously provide high-quality beams for 4th generation synchrotron radiation sources and FELs is desirable. The design of a 1.6-cell S-band 2998-MHz RF gun and beam dynamics optimization of a relevant beamline are presented in this paper. Beam dynamics simulations were performed by combining ASTRA and the multi-objective genetic algorithm NSGA II. The effects of the laser pulse shape, half-cell length of the RF gun, and RF parameters on the output beam quality were analyzed and compared. The normalized transverse emittance was optimized to be as low as 0.65 and 0.92 mm · mrad when the bunch charge was as high as 1 and 2 nC, respectively. Finally, the beam stability properties of the photoinjector, considering misalignment and RF jitter, were simulated and analyzed.

Full Text

Design of an S-Band Photoinjector with High Bunch Charge and Low Emittance Based on Multi-Objective Genetic Algorithm

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Abstract

High-brightness electron beams are essential for driving LINAC-based free-electron lasers (FELs) and storage-ring-based synchrotron radiation light sources. The bunch charge and RMS bunch length at the LINAC exit critically determine the peak current, while the minimum transverse emittance is primarily established by the LINAC injector. Consequently, a photoinjector capable of delivering both high bunch charge and low emittance is highly desirable for simultaneously providing high-quality beams for fourth-generation synchrotron radiation sources and FELs. This paper presents the design of a 1.6-cell S-band 2998-MHz RF gun and the beam dynamics optimization of its associated beamline. Beam dynamics simulations were performed by combining ASTRA with the multi-objective genetic algorithm NSGA-II. The effects of laser pulse shape, RF gun half-cell length, and RF parameters on output beam quality were analyzed and compared. The normalized transverse emittance was optimized to values as low as 0.65 mm · mrad and 0.92 mm · mrad for bunch charges of 1 nC and 2 nC, respectively. Finally, the beam stability properties of the photoinjector were simulated and analyzed, taking into account misalignment and RF jitter.

Keywords: Electron linear accelerator; Photoinjector; Beam dynamics; Multi-objective genetic algorithm

1. Introduction

LINAC-based free-electron lasers (FELs) and storage-ring-based diffraction-limited storage rings (DLSRs) have become indispensable tools for exploring the microscopic world, advancing research in physics, chemistry, biology, materials science, and related fields [1-5]. Normal conducting RF (NCRF) photoinjectors are widely employed in FELs due to their low emittance and high brightness, as illustrated in Table 1 . The evolution of synchrotron radiation sources has progressed through three generations, with fourth-generation sources based on DLSRs representing the current frontier. These facilities achieve brightness levels two to three orders of magnitude higher than their third-generation predecessors [13]. Following the success of MAX-IV in Sweden [14], Sirius in Brazil has completed its first commissioning phase [15], and numerous other fourth-generation sources are under construction or in planning, including APS-U, SPring-8, ALS, Soleil, Diamond, HEPS, and HALS [16]. While thermal cathode injectors have been extensively used in synchrotron light sources [17], photoinjectors offer superior performance when higher beam brightness is required from the LINAC. S-band photoinjectors are currently operational at MAX-IV, HALF, and other facilities [18, 19].

This study describes a dual-use photoinjector designed to provide high-quality beams for both storage ring operation—where swap-out injection mode demands bunch charges exceeding 1 nC—and FEL applications, which favor low emittance [20-22]. Swap-out injection represents a promising alternative for DLSRs, where conventional off-axis cumulative injection becomes prohibitively difficult due to small dynamic apertures.

In photoinjector beam dynamics optimization, theoretical analysis can establish approximate parameter ranges, but more accurate results require optimization algorithms guided by theoretical principles. For multiparameter optimization in accelerator applications, multi-objective genetic algorithms (MOGA) and multi-objective particle swarm algorithms (MOPSO) represent mainstream approaches [23-30]. MOGA offers rapid convergence, while MOPSO generates greater solution diversity and possesses strong global search capabilities. For our eight-variable optimization problem, MOGA based on the non-dominated sorting genetic algorithm-II (NSGA-II) provides a reliable solution [31]. This algorithm reduces the complexity of non-dominated sorting and offers advantages in computational speed and convergence performance.

This paper presents a detailed design of the 1.6-cell S-band 2998-MHz RF gun and comprehensive beam dynamics optimization of the photoinjector. Section 2 discusses the RF gun design, focusing on achieving a flat axial field distribution, large separation between adjacent electromagnetic modes, and higher axial field relative to the cavity surface field. Section 3 employs NSGA-II and ASTRA for beam dynamics optimization, examining various laser pulse shapes, gun half-cell lengths, and RF gradients. Section 4 analyzes photoinjector stability in the presence of misalignment and RF jitter.

2. RF Design

This section describes a 1.6-cell S-band BNL/SLAC/UCLA photocathode RF gun [32]. Gun performance was enhanced by optimizing the Q factor, peak electric field on the cavity wall, adjacent mode separation, and axial electric field flatness. Electromagnetic field calculations were performed using SUPERFISH [33], which enables rapid frequency tuning to the target value, balances the axial electric field between half-cell and full-cell, and generates field maps for beam dynamics simulations.

During optimization, the ratio of peak electric field on the wall (E_{max}) to the field on the photocathode (E_c) can be reduced by employing an elliptical iris rather than a circular one. Another critical parameter is the separation between adjacent modes. Both 0-mode and π-mode exist in the RF gun. The 0-mode cannot accelerate the electron beam, causing emittance growth and additional energy spread [34]. Therefore, the separation between 0-mode and π-mode should be increased by enlarging the iris aperture or reducing the disk thickness.

Figure 1 [Figure 1: see original paper] illustrates the influence of iris aperture (r_a) and axial ratio ($t = t_a/t_b$) on RF parameters. As shown in Fig. 1(b), with the major and minor axes of the elliptical iris fixed at $t_a = 16$ mm and $t_b = 10$ mm, the mode separation increases dramatically from 5 MHz to 75 MHz as r_a expands from 11 mm to 20 mm, while the Q factor improves by 4%. Figure 1(c) demonstrates the effect of axial ratio. With aperture $r_a = 18$ mm and minor axis $t_b = 10$ mm held constant, E_{max} decreases from 5% above E_c to 8% below E_c, and mode separation increases from 40 MHz to 49 MHz as the major axis t_a increases from 10 mm to 16 mm.

In the LCLS RF gun, cavity structure optimization increased the 0-mode to π-mode separation from 3.5 MHz to 15 MHz [35]. Consequently, the 0-mode electric field amplitude on the photocathode decreased from 10% of the axial field to less than 3%, significantly improving beam performance. A larger frequency separation (>40 MHz) between the two resonant modes further suppresses 0-mode excitation during transients in the pulsed regime, enabling a uniform accelerating field along the bunch train and controlling field gradient variation on the photocathode to approximately 0.1%—particularly crucial for short-pulse, high-repetition-rate beams [36]. The final design parameters were selected as $t_a = 16$ mm, $t_b = 10$ mm, and $r_a = 18$ mm. Table 2 lists the optimized RF gun parameters, and Fig. 2 [Figure 2: see original paper] shows the relationship between normalized axial electric field and surface field along the axis. The field flatness (ratio between half-cell and full-cell fields) equals 1, with the cavity surface field lower than the axial field. The axial electric field map extracted from SUPERFISH serves as input for ASTRA beam dynamics optimization [37].

3. Beam Dynamics

An S-band photoinjector system typically comprises a drive laser, photocathode RF gun, and focusing solenoids, as depicted in Fig. 3 [Figure 3: see original paper]. The laser pulse stimulates the photocathode to generate electron beams, which are rapidly accelerated to relativistic velocities by the high-gradient RF field in the gun. Solenoids focus the beam transversely and align the bunch slice distribution in transverse phase space to compensate for emittance growth from linear space charge forces [38]. With subsequent acceleration in downstream structures, the beam becomes highly relativistic at the injector exit, where space charge effects no longer induce significant emittance growth.

Ideally, the beam should have minimal bunch length, low emittance, small transverse size, and low energy spread. Beam quality depends on numerous parameters, including laser pulse transverse and temporal profiles, RF field gradient and phase in the photocathode gun, solenoid magnetic field strengths, and accelerating cavity RF gradients and phases. Under identical initial bunch length conditions, energy spread is primarily determined by RF phase in the S-band traveling wave (TW) accelerating cavity. Minimum energy spread at the injector exit is achieved when the RF phase approaches the on-crest position. Transverse beam size can be readily adjusted using focusing elements such as quadrupoles. Consequently, the primary optimization objectives are minimizing

RMS bunch length and normalized transverse emittance.

To enhance simulation efficiency, the multi-objective genetic algorithm NSGA-II was coupled with ASTRA to identify optimal solutions. The main optimization objectives are RMS bunch length and normalized transverse emittance, both to be minimized for improved beam brightness. Constraints on output RMS transverse bunch size and relative energy spread were imposed to ensure beam quality and transmission efficiency. A drive laser pulse with a plateau temporal distribution was used, featuring a 10 ps full-width-at-half-maximum (FWHM) pulse length and 1 ps rise/fall time. Initial bunch charges of 1 nC and 2 nC were investigated. The bucking solenoid introduces a current opposite to the main solenoid to achieve vanishing magnetic field at the cathode, preventing emittance growth from magnetized beams [34]. The emittance contribution from magnetized beams was estimated at less than 0.003 mm · mrad for an 8 G magnetic field in our simulations, which does not affect the final optimization results.

The photocathode material's intrinsic thermal emittance was set to 0.9 mm · mrad/mm, based on measurements from metal photocathodes at LCLS and values for semiconductor materials [39, 40]. To balance computational time and accuracy, 10k macro-particles were used in beam dynamics simulations. Space charge fields were calculated on a cylindrical grid with 20 radial rings and 30 longitudinal slices, with a maximum time step of 1 ps. Each ASTRA cycle required approximately 7 minutes. The population size per generation was 120, with 100 total runs executed using parallel computation for 90 particle files simultaneously. Promising solutions were re-simulated with 100k macro-particles for detailed analysis.

3.1 Beam Dynamics Simulation at 1 nC

Emittance compensation using focusing solenoids effectively minimizes emittance growth from space charge forces, but only compensates for linear space charge effects. In practice, nonlinear space charge forces cause additional emittance growth. Theoretical analysis and experiments demonstrate that flat-top temporal distributions and transversely truncated Gaussian distributions with approximately 1-sigma truncation can linearize space charge effects [41]. The transverse laser profile can be shaped using a beam-shaping aperture (BSA) along the transport line from laser to photocathode. Figure 4 [Figure 4: see original paper] shows truncated Gaussian distributions with truncation ratios of 0.9, 1.1, and 1.5 sigma. Table 3 lists the parameter variables for NSGA-II-based optimization, with ranges narrowed from initial broader scans. Higher RF field gradients accelerate bunches to relativistic velocity more rapidly, suppressing emittance growth and beam expansion from space charge effects. For bunch charges exceeding 1 nC, Cs_2Te semiconductor photocathodes are preferred. However, the operating RF field gradient should be minimized to prolong photocathode lifetime [42]. Balancing bunch charge and RF gradient requirements, the gradient was set to 100 MV/m.

Figure 5 Figure 5: see original paper presents the resulting Pareto front of non-dominated solutions, revealing the trade-off between normalized transverse emittance and RMS bunch length. Additional simulations were performed for truncated Gaussian distributions with truncation ratios of 0.8, 1.0, 1.2, and 2.0 sigma. Figure 5(b) shows the achievable minimum emittance and corresponding beam size after truncation as functions of truncation ratio. The optimal normalized transverse emittance is 0.61 mm · mrad for 1-sigma truncation and 0.65 mm · mrad for 1.5-sigma truncation. Although 1.5-sigma truncation yields slightly higher minimum emittance, it significantly improves drive laser power utilization efficiency compared to 1-sigma truncation. Since laser efficiency is crucial for achieving high initial bunch charge, a transverse Gaussian distribution truncated at 1.5 sigma was selected for subsequent simulations.

According to Dowell's theory [43], for a pancake beam including the bunch's mirror charge field, thermal emittance can be expressed as $\epsilon_{th} = \sigma_{x,y}\sqrt{(\hbar\omega - \phi_w)}/(4E_0 \sin\phi)$, where $\sigma_{x,y}$ is the initial RMS transverse size, $\hbar\omega$ is the laser photon energy, ϕ_w is the work function, and $E_0 \sin\phi$ is the electric field on the photocathode during photoemission. Assuming a 2D radial uniform distribution for the initial bunch, thermal emittance is minimized when the beam radius satisfies $\sigma_{x,y} = E_0 \sin\phi$. For the optimized 1.6-cell S-band RF gun, the electric field during photoemission is approximately 41 MV/m, yielding an optimal beam radius of 0.94 mm for minimum thermal emittance, equivalent to an initial RMS beam size of 0.47 mm. This theoretical result aligns with simulation results shown in Fig. 5(b) across different Gaussian truncation ratios.

Using working points of 1.04 mm RMS bunch length and 1.5-sigma truncated transverse Gaussian distribution, 100k macro-particles were simulated. Figure 6 [Figure 6: see original paper] shows the evolution of normalized transverse emittance, RMS transverse size, average energy, and RMS bunch length along the photoinjector. The normalized transverse emittance is 0.65 mm · mrad with a peak current of 100 A. The 95% projected emittance is 0.56 mm · mrad, closely matching the slice emittance shown in Fig. 7 [Figure 7: see original paper]. The bunch mismatch factor is 1.09, near the ideal value of 1.0.

3.2 Beam Dynamics Simulation at 2 nC

Storage rings operating in swap-out injection mode require high bunch charge from the injector to increase average ring current. For example, the Wuhan Photon Source (WHPS) under design requires bunch charges up to 1.7 nC from the LINAC injector to achieve its design current of 500 mA via swap-out injection. The LINAC exit specifications demand normalized transverse emittance below 5 mm · mrad and relative energy spread below 0.3%. Additionally, the planned FEL requires normalized transverse emittance below 1 mm · mrad [44]. This section investigates beam dynamics optimization for an initial bunch charge of 2 nC. RF gun, solenoid, and TW structure positions were fixed based on 1 nC optimization results. The initial laser pulse maintained the 10 ps FWHM plateau temporal distribution with 1 ps rise/fall time, and the transverse Gaussian distribution was truncated at 1.5 sigma. NSGA-II optimization was performed by adjusting laser phase, initial beam size, RF field gradient and phase, and solenoid magnetic field strengths.

Figure 8 [Figure 8: see original paper] shows that the initial beam size should be approximately 0.696 mm to achieve minimum output emittance, consistent with the value calculated from $0.94 \sin\phi$. From the optimization results, working points were selected with 0.696 mm initial RMS beam size and 1.25 mm output bunch length. Macro-particles were increased to 100k for improved accuracy. Figure 9 [Figure 9: see original paper] demonstrates that the normalized transverse emittance reaches 0.92 mm · mrad with a peak current of 170 A at the photoinjector exit. These results indicate that injecting high bunch charges up to 2 nC with very low emittance into storage rings using full-energy LINAC injectors with photocathode RF guns is highly feasible.

3.3 Comparison of First-Cell Lengths in the Gun

Theoretically, the first-cell length in the gun is typically assumed to be 0.25λ [45], corresponding to one-quarter period of the cosinoidal temporal profile. A shorter half-cell length increases the acceleration field by positioning the beam near the on-crest RF phase due to reduced phase slippage time. This accelerates the electron bunch to relativistic velocity more quickly, reducing emittance growth from space charge effects [46]. However, a longer half-cell length provides greater longitudinal bunch compression and increased energy gain after the half-cell. Therefore, specific optimization is required to determine the optimal half-cell length. First-cell lengths of 0.2λ and 0.3λ were investigated, with simulation results presented in Table 4 . Figure 10 [Figure 10: see original paper] shows transverse emittance and RMS bunch length evolution along the photoinjector. Although the 1.4-cell RF gun's extraction field gradient at the photocathode surface is twice that of the 1.6-cell gun, its output beam energy at the gun exit is lower. The 1.6-cell gun produces shorter output bunch length with equivalent emittance at 1 nC and lower emittance at 2 nC.

3.4 Field Gradient in RF Gun

Higher RF gun field gradients more effectively suppress emittance growth from space charge effects, yielding lower output emittance and shorter bunch length at the photoinjector exit. State-of-the-art S-band RF guns have achieved field gradients of 120 MV/m [36], with stable operation typically around 100 MV/m [7]. Semiconductor photocathode lifetime is strongly dependent on gun vacuum level, which is sensitive to electric field gradient. Consequently, operating RF field gradients should be minimized. The effects of 90 MV/m, 100 MV/m, and 120 MV/m field gradients on beam quality at 1 nC and 2 nC were investigated, with results shown in Fig. 11 [Figure 11: see original paper]. For 1 nC, minimum normalized transverse emittances were 0.83, 0.74, and 0.65 mm · mrad, with RMS bunch lengths of 0.99, 1.06, and 1.06 mm, respectively, as field gradient increased from 90 MV/m to 120 MV/m. For 2 nC, corresponding minimum emittances were 1.26, 1.13, and 1.02 mm · mrad, with bunch lengths of 1.22, 1.25, and 1.18 mm. For our application, RF gradients of 100 MV/m or even 90 MV/m are viable, as ASTRA simulations demonstrate that beam emittances as low as 0.7 and 1.0 mm · mrad can be achieved with initial bunch charges of 1 nC and 2 nC, respectively, meeting beam quality requirements.

3.5 Field Flatness in RF Gun

Field flatness is crucial for achieving maximum beam energy and uniform RF power dissipation in the gun. Optimal field flatness occurs when maximum field amplitudes are equal in each cell (flatness = 1). However, mechanical errors during gun fabrication inevitably cause field imbalances between half- and full-cells. The effects of field flatness values of 0.9, 1.0, and 1.1 on emittance at 1 nC and 2 nC were studied. Axial field distributions for a 100 MV/m photocathode field gradient are shown in Fig. 12 [Figure 12: see original paper], with beam dynamics simulation results presented in Table 5 . The results indicate minimal influence of field flatness on output emittance within the studied range.

4. Stability Analysis

In a photoinjector, component misalignment—including displacement and rotation errors of the gun, traveling-wave acceleration cavities, and solenoids—can cause emittance growth. The sensitivity of emittance to component misalignment must be understood to control these errors within acceptable limits. RF jitter also induces beam parameter fluctuations around nominal values.

4.1 Mechanical Errors

Displacement or rotation errors cause more electrons to experience transverse defocusing fields and shift the bunch center away from the solenoid's axial focusing magnetic field, leading to transverse emittance growth. Table 6 quantifies emittance growth due to mechanical errors for bunch charges of 1 nC and 2 nC. At low beam energy, misalignment of the RF gun and solenoids significantly impacts emittance growth. In the higher-energy section, misalignment of acceleration tubes (within 1 mm or 1 mrad) has a smaller effect on emittance growth.

4.2 Operation Errors

During photoinjector operation, parameter jitter affects normalized transverse emittance, beam size, and beam energy. A 1000-shot simulation was performed with 100k macro-particles, varying bunch charge, laser timing, laser spot size, laser offset, RF phases and amplitudes, and magnetic field strengths. Each parameter was sampled uniformly within its error range, as specified in Table 7 . Statistical results for 1 nC and 2 nC are shown in Figs. 13 and 14 [FIGURE:13, FIGURE:14]. When parameter errors are controlled within the ranges specified in Table 7, the photoinjector beam stability meets the requirements of the Wuhan Photon Source.

5. Results and Discussion

This study presents a systematic design for an S-band photoinjector capable of delivering high-bunch-charge beams for storage ring swap-out injection and high-brightness beams for FELs. A simulation method coupling ASTRA and NSGA-II was developed and demonstrated as an efficient approach for obtaining globally optimal solutions in beam dynamics design. Through iterative narrowing of the scanning range, the global optimum was progressively approached. With an RF gun field gradient of 100 MV/m, the normalized transverse emittance at the photoinjector exit reached 0.65 mm · mrad and 0.92 mm · mrad for 1 nC and 2 nC, respectively. At 2 nC, all hardware positions remained identical to those optimized for 1 nC. The results demonstrate that high beam quality—including short bunch length and low emittance—can be achieved across a wide range of bunch charges by simply adjusting photoinjector operating parameters. Furthermore, the beam stability analysis provides theoretical guidance for controlling mechanical and operational errors in practical systems.

Contributions Statement: All authors contributed to study conception and design. Material preparation, data collection, and analysis were performed by Ze-Yi Dai, Yuan-Cun Nie, Zi Hui, Lan-Xin Liu, and Zi-Shuo Liu. The first draft was written by Ze-Yi Dai, and all authors commented on previous versions and approved the final manuscript.

References

1. M. Eriksson, J.F. van der Veen, C. Quitmann et al., Diffraction-limited storage rings–a window to the science of tomorrow. J. Synchrotron Rad. 21, 837–842 (2014). https://doi.org/10.1107/S1600577514019286

2. A. Bjorling, S. Kalbfleisch, M. Kahnt et al., Ptychographic characterization of a coherent nanofocused X-ray beam. Opt. Express 28, 5069–5076 (2020). https://doi.org/10.1364/OE.386068

3. [Reference missing in original]

4. C. Bostedt, S. Boutet, D.M. Fritz et al., LINAC coherent light source: the first five years. Rev. Mod. Physics 88, 015007 (2016). https://doi.org/10.1103/RevModPhys.88.015007

5. C. Feng, H.X. Deng, Review of fully coherent free-electron lasers. Nucl. Sci. Tech. 29, 160 (2018). https://doi.org/10.1007/s41365-018-0490-1

6. Z. Zhao, D. Wang, Q. Gu et al., SXFEL: A Soft X-ray free electron laser in China. Synchrotron Rad. News 30, 29–33 (2017). https://doi.org/10.1080/08940886.2017.1386997

7. L.M. Zheng, Y.C. Du, Z. Zhang et al., Development of S-band photocathode RF guns at Tsinghua University. Nucl. Instrum. Meth. Phys. Res. Sect. A 834, 98–107 (2016). https://doi.org/10.1016/j.nima.2016.07.015

8. P. Emma, R. Akre, J. Arthur et al., First lasing and operation of an ångstrom-wavelength free-electron laser. Nat. Photonics 4, 641–647 (2010). https://doi.org/10.1038/nphoton.2010.176

9. H.S. Kang, C.K. Min, H. Heo et al., Hard X-ray free-electron laser with femtosecond-scale timing jitter. Nat. Photonics 11, 708–713 (2017). https://doi.org/10.1038/s41566-017-0029-8

10. J. Lee, I.S. Ko, J.H. Han et al., Parameter optimization of PAL-XFEL injector. J. Korean Phys. Soc. 72, 1158–1165 (2018). https://doi.org/10.3938/jkps.72.1158

11. C. Milne, T. Schietinger, M. Aiba et al., SwissFEL: the Swiss X-ray free electron laser. Appl. Sci. 7, 720 (2017). https://doi.org/10.3390/app7070720

12. T. Schietinger, M. Pedrozzi, M. Aiba et al., Commissioning experience and beam physics measurements at the SwissFEL injector test facility. Phys. Rev. Accel. Beams 19, 100702 (2016). https://doi.org/10.1103/PhysRevAccelBeams.19.100702

13. M. Bei, M. Borland, Y. Cai et al., The potential of an ultimate storage ring for future light sources. Nucl. Instru. Meth. Phys. Res. Sect. A 622, 518–535 (2010). https://doi.org/10.1016/j.nima.2010.01.045

14. P.F. Tavares, E. Al-Dmour, A. Andersson et al., Commissioning and first-year operational results of the MAX IV 3 GeV ring. J. Synchrotron Rad. 25, 1291–1316 (2018). https://doi.org/10.1107/S1600577518008111

15. K. Duhrkop, M. Fleischauer, M. Ludwig et al., SIRIUS 4: a rapid tool for turning tandem mass spectra into metabolite structure information. Nat. Methods 16, 299–302 (2019). https://doi.org/10.1038/s41592-019-0344-8

16. R. Hettel, DLSR design and plans: an international overview. J. Synchrotron Rad. 21, 843–855 (2014). https://doi.org/10.1107/S1600577514011515

17. Y.C. Nie, C. Liebig, M. Hüning et al., Tuning of 2.998 GHz S-band hybrid buncher for injector upgrade of LINAC II at DESY. Nucl. Instru. Meth. Phys. Res. Sect. A 761, 69–78 (2014). https://doi.org/10.1016/j.nima.2014.05.043

18. J. Andersson, F. Curbis, L. Isaksson et al., The Pre-Injector and Photocathode Gun Design for the MAX IV SXL. in Proceedings of IPAC2019, Melbourne, Australia, 2064–2066 (2019)

19. W.X. Wang, C. Li, Z.G. He, et al., Commissioning the photocathode radio frequency gun: a candidate electron source for Hefei Advanced Light Facility. Nucl. Sci. Tech. 33, 1–9 (2022). https://doi.org/10.1007/s41365-022-01000-6

20. Y. Jiao, G. Xu, X.H. Cui et al., The HEPS project. J. Synchrotron Rad. 25, 1611–1618 (2018). https://doi.org/10.1107/S1600577518012110
21. S. Henderson, Status of the APS upgrade project. in Proceedings of IPAC 2015, Richmond, VA, USA, 1791–1793 (2015)
22. D. Wang, K.L.F. Bane, S. Santis et al., Single bunch instability simulations in the storage ring of the ALS-U project. in Proceedings of IPAC2021, Campinas, SP, Brazil, 2783–2785 (2021)
23. L. Yang, D. Robin, F. Sannibale et al., Global optimization of an accelerator lattice using multiobjective genetic algorithms. Nucl. Instru. Meth. Phys. Res. Sect. A 609, 50–57 (2009). https://doi.org/10.1016/j.nima.2009.08.027
24. J. Wan, P. Chu, Y. Jiao, Neural network-based multiobjective optimization algorithm for nonlinear beam dynamics. Phys. Rev. Accel. Beams 23, 081601 (2020). https://doi.org/10.1103/PhysRevAccelBeams.23.081601
25. C. Meng, O.Z. Xiao, S.L. Pei et al., Optimization of Klystron efficiency with MOGA. in Proceedings of IPAC2018, Vancouver, BC, Canada,2419–2421 (2018)
26. X. Pang, L.J. Rybarcyk, Multi-objective particle swarm and genetic algorithm for the optimization of the LANSCE linac operation. Nucl. Instru. Meth. Phys. Res. Sect. A 741, 124–129 (2014). https://doi.org/10.1016/j.nima.2013.12.042
27. H. Feng, S. De Santis, K. Baptiste et al., Proposed design and optimization of a higher harmonic cavity for ALS-U. Rev. Sci. Instr. 91, 014712 (2020). https://doi.org/10.1063/1.5135955
28. R. Bartolini, M. Apollonio, I.P.S. Martin, Multiobjective genetic algorithm optimization of the beam dynamics in LINAC drivers for free electron lasers. Phys. Rev. ST Accel. Beams 15, 030701 (2012). https://doi.org/10.1103/PhysRevSTAB.15.030701
29. C. Gulliford, A. Bartnik, I. Bazarov et al., Multiobjective optimization design of an RF gun based electron diffraction beam line. Phys. Rev. Accel. Beams 20, 033401 (2017). https://doi.org/10.1103/PhysRevAccelBeams.20.033401
30. I.V. Bazarov, C.K. Sinclair, Multivariate optimization of a high brightness dc gun photoinjector. Phys. Rev. ST Accel. Beams 8, 034202 (2005). https://doi.org/10.1103/PhysRevSTAB.8.034202
31. K. Deb, A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE trans. Evol. Comput. 6, 182–197 (2002). https://doi.org/10.1109/4235.996017
32. J. Rosenzweig, S. Anderson, K. Bishofberger et al., The neptune photoinjector. Nucl. Instru. Meth. Phys. Res. Sect. A 410, 437–451 (1998). https://doi.org/10.1016/S0168-9002(98)00175-2

33. K. Halbach, R. Holsinger, Superfish–a computer program for evaluation of RF cavities with cylindrical symmetry. Particle Accel. 7, 213–222 (1976)

34. [Reference missing in original]

35. C. Limborg-Deprey, L. Xiao, D. Dowell et al., Modifications on RF components in the LCLS injector. in Proceedings of PAC2005, Knoxville, Tennessee, 2233–2235 (2005)

36. D. Alesini, A. Battisti, M. Bellaveglia et al., Design, realization, and high power test of high gradient, high repetition rate brazing-free S-band photogun. Phys. Rev. Accel. Beams 21, 112001 (2018). https://doi.org/10.1103/PhysRevAccelBeams.21.112001

37. [Reference missing in original]

38. B.E. Carlsten, New photoelectric injector design for the Los Alamos National Laboratory XUV FEL accelerator. Nucl. Instru. Meth. Phys. Res. Sect. A 285, 313–319 (1989). https://doi.org/10.1016/0168-9002(89)90472-5

39. Y. Ding, A. Brachmann, F.J. Decker et al., Measurements and simulations of ultralow emittance and ultrashort electron beams in the LINAC coherent light source. Phys. Rev. Lett. 102, 254801 (2009). https://doi.org/10.1103/PhysRevSTAB.15.030701

40. P.W. Huang, H. Qian, Y. Du et al., Photoemission and degradation of semiconductor photocathode. Phys. Rev. Accel. Beams 22, 123403 (2019). https://doi.org/10.1103/PhysRevAccelBeams.22.123403

41. F. Zhou, A. Brachmann, P. Emma et al., Impact of the spatial laser distribution on photocathode gun operation. Phys. Rev. ST Accel. Beams 15, 090701 (2012). https://doi.org/10.1103/PhysRevSTAB.15.090701

42. S. Lederer, S. Schreiber, Cs2Te photocathode lifetime at flash and European XFEL. in Proceedings of IPAC2018, Vancouver, BC, Canada, 2496–2498 (2018)

43. D.H. Dowell, J.F. Schmerge, Quantum efficiency and thermal emittance of metal photocathodes. Phys. Rev. ST Accel. Beams 12, 074201 (2009). https://doi.org/10.1103/PhysRevSTAB.12.074201

44. H.H. Li, J. Wang, L. Tang et al., Project of Wuhan photon source. in Proceedings of IPAC2021, Campinas, SP, Brazil, 346–349 (2021)

45. J.K. Kim, RF and space-charge effects in laser-driven RF electron guns. Nucl. Instru. Meth. Phys. Res. Sect. A 275, 201–218 (1989). https://doi.org/10.1016/0168-9002(89)90688-8

46. E. Pirez, P. Musumeci, J. Maxson et al., S-band 1.4 cell photoinjector design for high brightness beam generation. Nucl. Instru. Meth. Phys. Res. Sect. A 865, 109–113 (2017). https://doi.org/10.1016/j.nima.2016.08.063