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Development and Characterization of a Superconducting Electron Accelerator with Wide-Range Tunable Dose Rate for Flash Effect Research

Jianhan Sun, PhD[1,2], Juntao Liu, PhD[1], Jianfeng Lv, PhD[1], Mengyi Tai, PhD[1], Yibao Zhang[2] and Senlin Huang, PhD[1]
[1]Peking University, [2]Peking University Cancer Hospital & Institute

ABSTRACT

FLASH radiotherapy (FLASH-RT) protects normal tissues while preserving anti-tumor effects, with its efficacy heavily governed by radiation physical parameters. This work introduces us system, a superconducting electron accelerator platform dedicated to FLASH-RT biological and preclinical research. Equipped with a complete superconducting acceleration, beam regulation and testing system, the platform delivers stable 1–20 MeV electron beams and corresponding X-rays, covering single-pulse, macro-pulse and continuous wave temporal modes. Core parameters including dose rate, pulse width and duty cycle can be flexibly tuned over multiple orders of magnitude. It achieves ultra-high maximum dose rates up to 3.98 × 10 Gy/s for 2 MeV electrons and 1.74 × 10 Gy/s for 6 MeV X-rays, with stable output across conventional and FLASH modes and a dose deviation below 5%. Successful cell and mouse experiments verified its biological research capability. As a fully adjustable FLASH irradiation platform, it supports systematic exploration of beam parameter-related biological mechanisms and serves as a reliable interdisciplinary tool for radiobiological study and translational radiation medical research.

CONTACT

Jianhan Sun
State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University
sunjianhan@stu.pku.edu.cn
+86 15865561326

INTRODUCTION

To investigate the potential impact of dose rate, beam energy, and temporal structure on the FLASH effect, an irradiation platform providing widely tunable dose rate and energy range is desirable. This work aims to develop and characterize a superconducting accelerator-based irradiation platform with widely tunable dose rate and beam energy for comprehensive FLASH radiobiology and pre-clinical studies.

Table 1. Operation parameters of Superconducting electron accelerator system

	electron gun beamline	main-accelerator beamline
Beam energy	1-3 MeV	3-20 MeV
Bunch charge*	0.1 fC -260 pC	
Beam current (maximum)*	5 mA (CW)	1 mA (10% duty cycle)
Micro-pulse repetition rate	1 MHz, 81.25 MHz	
Macro-pulse repetition rate	0.1 Hz to 1 MHz	
Micro-pulse pulse width	About 10 ps	
Duty-cycle	0 - 100%	
Dose conversion relationship	D (Gy) = 7.96 × 10^7 Q (C) (2MeV, electron) D (Gy) = 2.15 × 10^6 Q (C) (2MV, X-ray)	D (Gy) = 3.08 × 10^8 Q (C) (6 MeV, electron) D (Gy) = 1.74 × 10^6 Q (C) (6 MV, X-ray)
Instantaneous dose rate (in RCF)**	265.33 Gy/s ~ 6.90 × 10^8 Gy/s (2 MeV, electron) 7.17 Gy/s ~ 1.86 × 10^6 Gy/s (2 MV, X-ray)	1.03 × 10^3 Gy/s ~ 2.67 × 10^9 Gy/s (6 MeV， electron) 5.80 Gy/s ~ 1.51 × 10^7 Gy/s (6MV， X-ray)
Average dose rate (in RCF, maximum)***	3.98 × 10^5 Gy/s (2 MeV, electron) 1.07 × 10^4 Gy/s (2 MV, X-ray)	3.08 × 10^5 Gy/s (6 MeV, electron) 1.74 × 10^4 Gy/s (6 MV, X-ray)

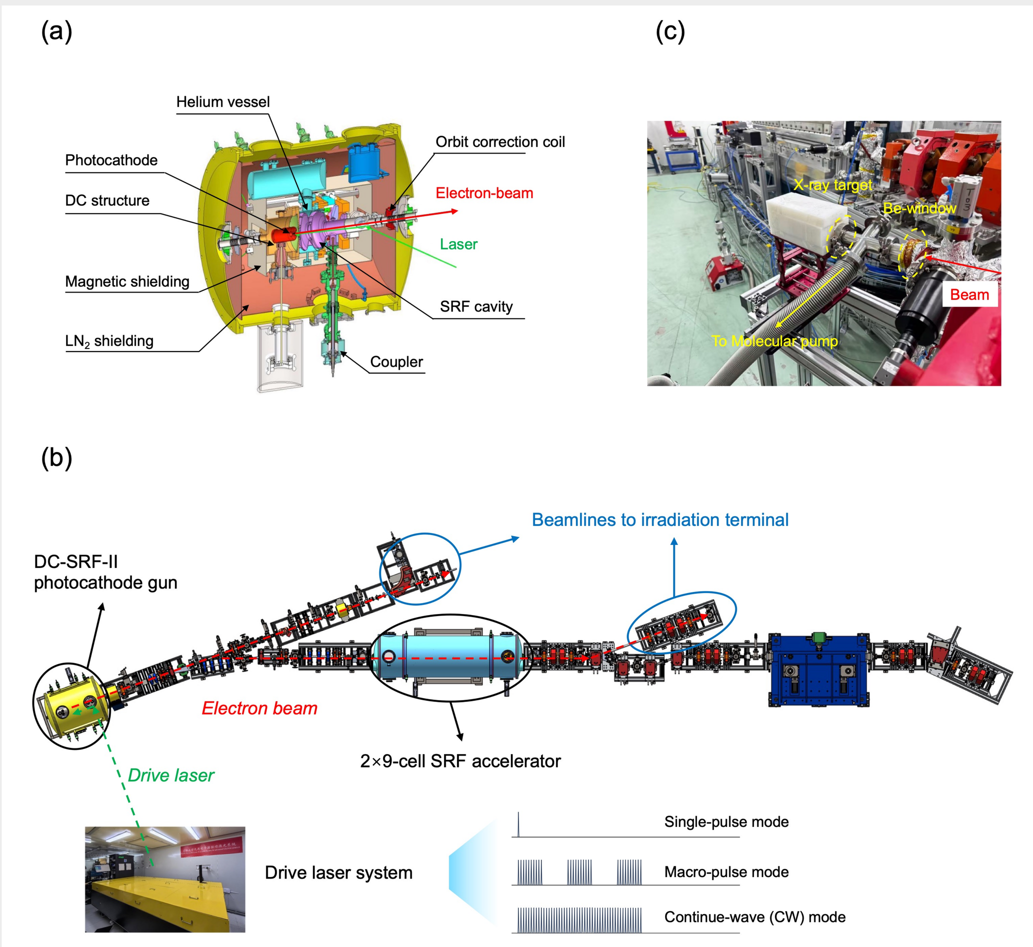


Figure 1. Generation, acceleration, and transmission of the beam. (a) 3D structure of DC-SRF-II photocathode gun. (b) Diagram of the electron gun and main-accelerator beamline. The drive laser system was fully enclosed and located in a separate cleanroom from accelerators, connected via a vacuum beam pipe. The electron beam generated by the electron gun can either be directly extracted or extracted after further accelerated by the main-accelerator. Inset illustrate three achievable beam temporal profiles. (c) Detachable X-ray conversion target, located at the beamline exit.

METHODS AND MATERIALS

An irradiation system consisting of a DC–SRF photocathode electron gun, a 2×9-cell superconducting linac, and integrated beam transport, control, and diagnostic modules was constructed. Electron energy and bunch charge were adjusted by controlling laser phase and RF amplitude and phase. Dosimetry was performed using Faraday cups, scintillator screens, fast current transformers, and radiochromic films under different beam modes. Dose and dose rate were controlled by varying pulse structure and bunch charge. Dedicated irradiation terminals for cell and small-animal experiments were established.

RESULTS

Electron beams with energies ranging from 1 to 20 MeV and the corresponding X-rays can be stably generated, covering three temporal structures: single pulse, macro-pulse, and continuous wave. Key parameters such as single-pulse dose, pulse width, and duty cycle can be independently and continuously adjusted across several orders of magnitude. At 2 MeV, the maximum dose rate of eletrons and X-rays exceed 3.98 × 10^5 Gy/s and 1.07 × 10^4 Gy/s respectively, at 6 MeV, these values are 3.08 × 10^5 Gy/s and 1.74 × 10^4 Gy/s.The tested dose rates remain stable across several orders of magnitude from conventional dose rate (CONV) to FLASH mode, with a total dose deviation of less than 5%. Verification biological experiments under different dose rates have been successfully carried out on cells and mice, and preliminary biological differences were observed.

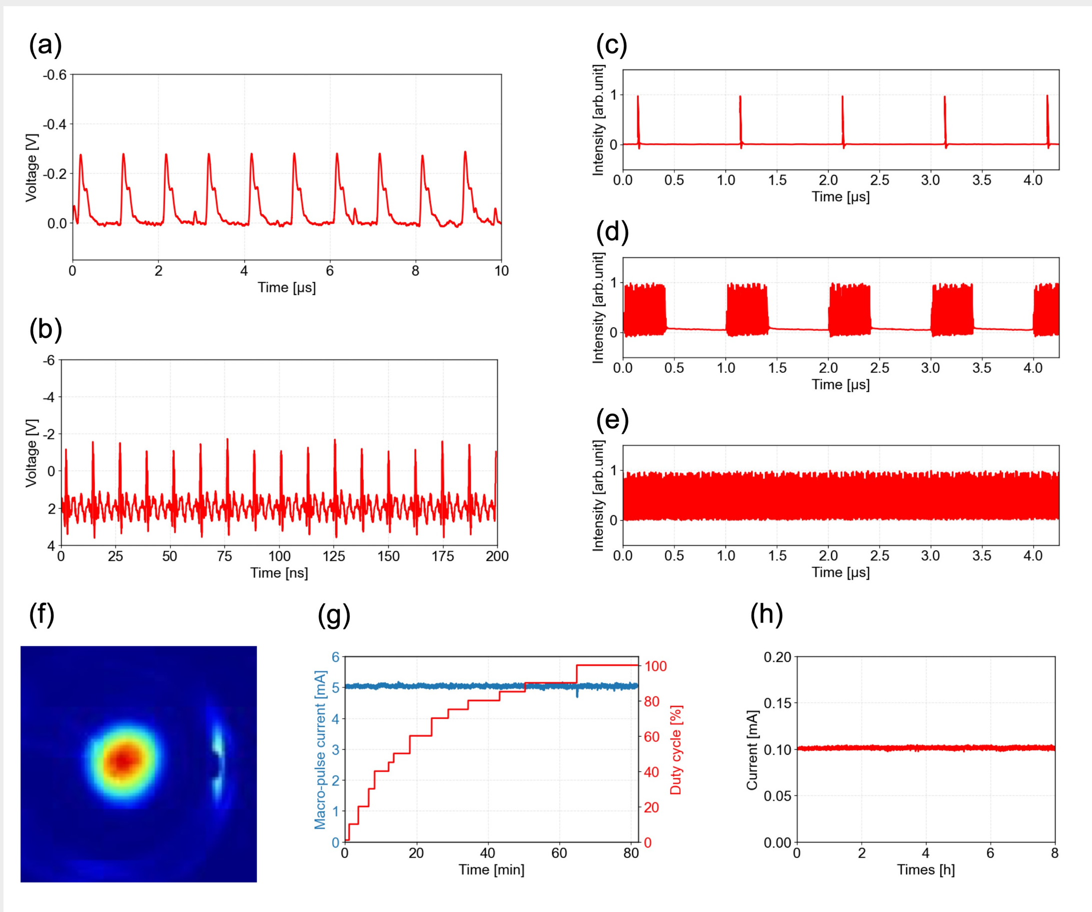


Figure 2. Beam characteristics. (a) Waveforms of micro-pulses recorded by FCT at 1 MHz mode, and (b), at 81.25 MHz mode. (c) Pulse temporal profiles in single-pulse mode, (d) macro-pulse mode, and (e) CW mode. (f) Transverse distribution of electron beam spots recorded by a YAG screen. (g) Adjusting the duty cycle of macro-pulses to gradually achieve 5 mA CW operation. The left axis represents the average current intensity within a macro-pulse, and the right axis represents the duty cycle. (h) Current data for 0.1 mA CW operation over 8 hours. Panels (f) and (g) were recorded by ICT.

CONCLUSIONS

This system enables extensive modulation of multiple beam parameters on a single platform to cover the full physical parameter matrix involved in FLASH. This platform allows systematic investigation into the influence rules of beam currents on biological effects, and serves as a testing platform for the transformation of technologies such as radiation physics and chemistry. It thus functions as an interdisciplinary center for radiobiology, preclinical research and medical technology.

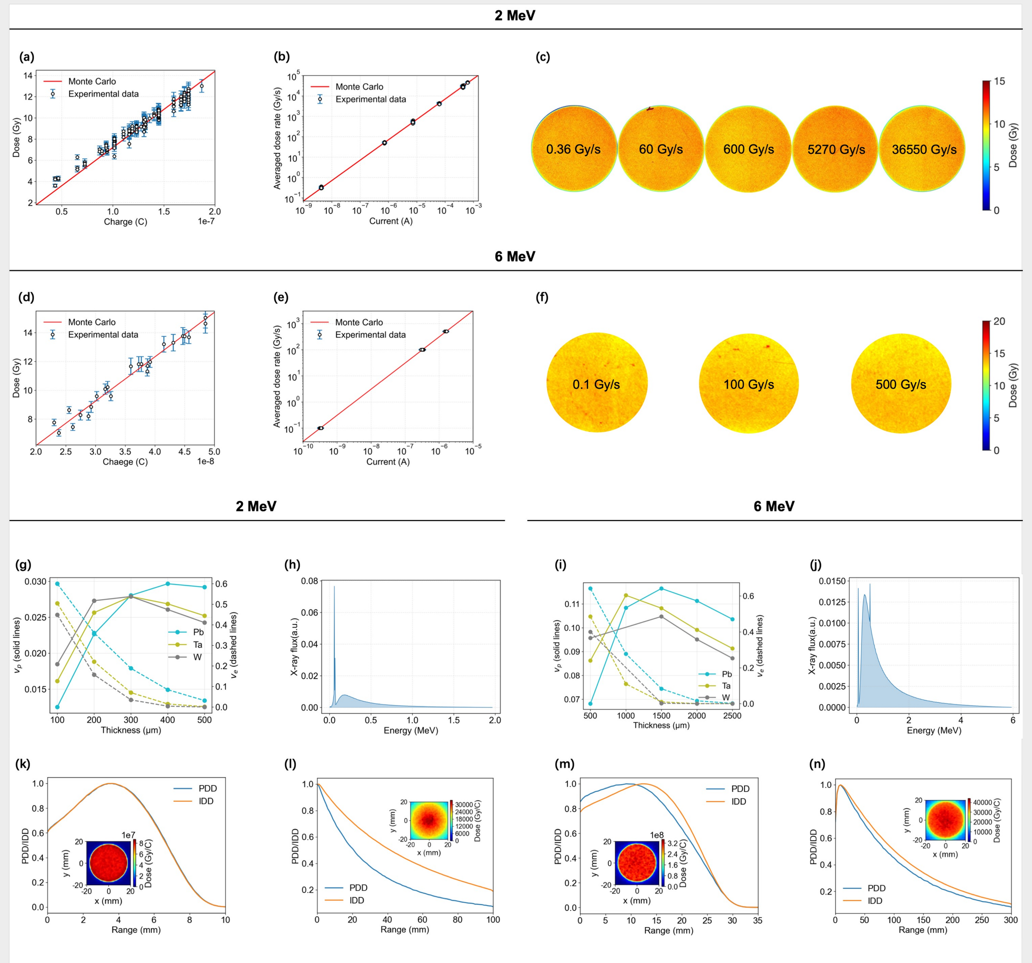
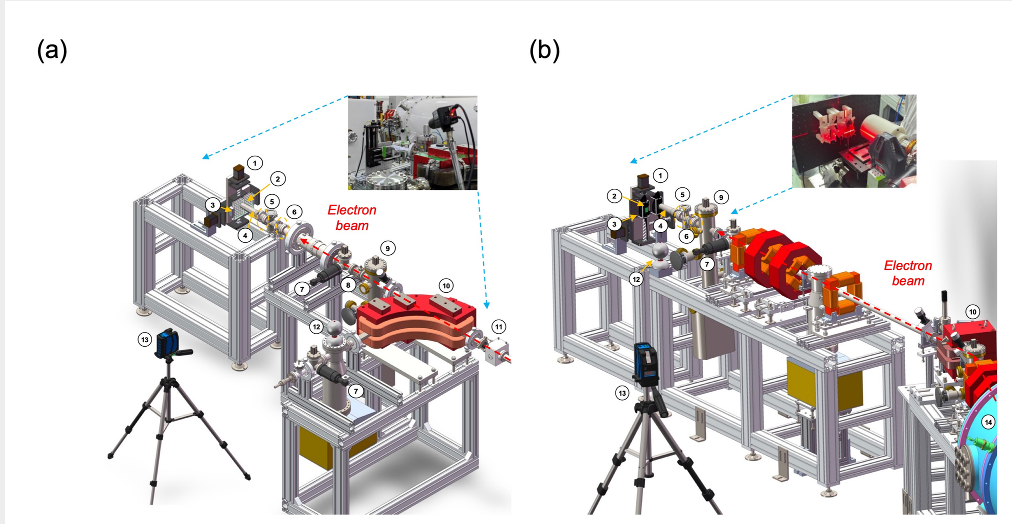


Figure 3. Dosimetric characterization. (a) Stability comparison of a 2 MeV electron beam under different dose rates. (b) and (c) Experimental calibration of dose/dose rate versus beam parameters. (d–f) Data for 6 MeV electron beam irradiation. (g) and (h) Bremsstrahlung efficiency and electron transmission coefficient for the 2 MeV electron beam, along with the energy spectrum of bremsstrahlung X-rays using a 300 µm W target. (i) and (j) Corresponding data for the 6 MeV electron beam, with spectra obtained using a 1500 µm Ta target. (k) and (l) PDD/IDD curves for 2 MeV electron irradiation and 2 MV photons; insets show surface dose distributions in a water phantom. (m) and (n) Data for 6 MeV electron irradiation and 6 MV photons. Panels (a-f) present experimental results, while (g-n) are from Monte-Carlo simulations.



1. X-Y 2D translation stages, 2. Irradiation samples (panel a: cell plates; panel b: mices) and RCF films, 3. Sample holder, 4. Beam collimator, 5. Removable X-ray conversion target, 6. Be-window, 7. Fluorescent screen and camera, 8. Fast Current Transformer (FCT), 9. Faraday cup (FC), 10. Analyzing magnet, 11. Beam Position Monitor (BPM), 12. Camera, 13. Laser level, 14. Main accelerator.

Figure 4. Schematic diagram of the irradiation terminal. (a) and (b) are located in the electron gun beamline and the main-accelerator beamline, respectively. The panels are on-site photos of the corresponding regions.

REFERENCES

1. Sun J, Lv J, Tian S, Liu J, Zhang Z, Xu H, et al. Dosimetry study of high repetition rate 2 MeV electron beam from a continuous-wave photocathode gun. Phys Scr 2025;100:065010. https://doi.org/10.1088/1402-4896/add57a.
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