THE COLLIMATOR SYSTEM FOR REDUCING THE DARK CURRENT IN NSRRC PHOTOINJECTOR

An-Ping Lee, Ming-Chang Chou, Yi-Chieh Chang, Wei-Yuan Chiang, Hsin-Pai Hsueh
National Synchrotron Radiation Research Center, Hsinchu, Taiwan
Shan-You Teng, Department of Physics, National Central University, Taoyuan, Taiwan

Abstract

The NSRRC photo-injector generates ultrashort electron beams to produce superradiant radiation in the 100–500 µm range using a gap-tunable U100 planar undulator. The system comprises an S-band, laser-driven photocathode RF gun equipped with a compensation solenoid and a 5-meter-long linear accelerator (linac) that employs velocity bunching to create sub-picosecond electron beams. Under certain conditions, electrons emitted from the cathode surface can be accelerated to higher energies, while the main beam continues to gain energy in the linac. These stray electrons may strike the vacuum chamber, generating unwanted radiation that poses risks to accelerator components and radiation safety. To mitigate dark current, a collimator was installed between the photocathode gun and the linac to intercept these electrons before transport. This report presents experimental results alongside simulations, demonstrating the effectiveness of the collimator.

INTRODUCTION

The coherent terahertz (THz) facility at NSRRC is a superradiant THz source powered by a relativistic, sub-picosecond, high-brightness electron beam generated by a photoinjector [1,2]. The facility is designed to deliver MW-level superradiant THz radiation for scientific users, covering wavelengths from 100 to 500 µm. As illustrated in Fig. 1, the photocathode injector primarily consists of a 2998 MHz photocathode RF gun driven by a high-pulse-energy, 266 nm ultraviolet laser with a few-picosecond pulse width, and a 5.2 m long 2998 MHz booster linac. A gun solenoid is installed to control the transverse emittance of the electron beam. In operation, a high charge density photoelectron beam is emitted from a copper cathode and accelerated to 2.5 MeV by the RF field at 60 MV/m at the gun exit, thereby reducing the detrimental effects of space-charge forces on beam quality. To further mitigate space-charge effects, the downstream booster linac increases the beam energy to approximately 25 MeV.

However, the strong accelerating field in the gun cavity can induce field emission from the copper surface. These field-emitted electrons are the primary source of background current, commonly referred to as dark current. Some electrons emitted under conditions similar to those of the main beam can be further accelerated by the RF structures to high energies. These uncontrolled electrons then strike the metallic walls of the accelerator vacuum chamber, becoming a major source of excessive ionizing radiation. Effective mitigation of radiation dose induced by dark current can be achieved by removing unwanted particles in the low-energy region of the accelerator. This is best accomplished by introducing a collimator system between the electron gun and the first linac. Positioning the collimator upstream of the linac, where the beam energy is low, minimizes radiological activation, since particle losses at low energy are far less detrimental than those occurring at higher energies later in the accelerator. In this work, we conduct simulations to evaluate the collimator's effectiveness in suppressing dark current and subsequently install the collimator on the photoinjector system to measure the dark current under operational conditions. The experimental measurements are then compared with the simulation results to verify the collimator's blocking performance.

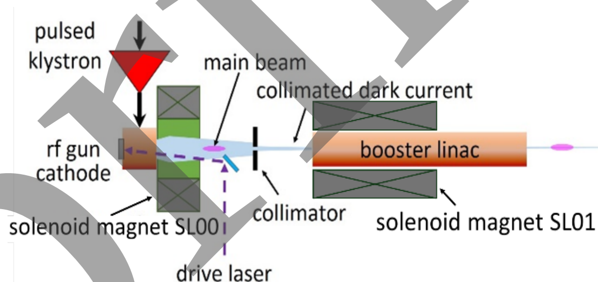

Figure 1: Schematic layout of the NSRRC photoinjector with a collimator installed to mitigate the entry of field-emitted electrons from the rf gun into the booster linac.[3]

DARK CURRENT SIMULATION

In earlier studies [3], a photoinjector system model was constructed by integrating a two-dimensional field map of the photocathode RF gun with the three-dimensional space-charge tracking code IMPACT-T, thereby enabling simulations of both the primary electron beam and the accompanying dark current. Building upon this established framework, the present work applies the same model while adopting the system parameters corresponding to actual operating conditions used for the generation of ultra-short electron beams. This approach allows us to investigate, under realistic circumstances, the effectiveness of a collimator in suppressing dark current.

In the IMPACT-T simulations, the main beam is modeled as a 250-pC electron bunch represented by 100,000 macroparticles, with both space-charge and image-charge effects included. A zero-momentum spread is assumed. The initial transverse distribution of field-emission electrons is calculated using the Fowler–Nordheim equation, which depends on the RF gun cavity field distribution at the cathode surface. Electrons are assumed to be uniformly distributed over an initial longitudinal interval, such that the RF phase experienced by the first emitted particle differs by 90° from that of the last particle.

The two-dimensional electric field distribution of the photocathode RF gun is obtained using Superfish while the solenoid magnetic field profile is calculated with the POISSON code. The peak on-axis electric field is set to 60 MV/m. The RF phase of the gun and the solenoid magnetic field strength are fixed at 275° and 0.149 T, respectively, based on experimentally established operating conditions for generating ultrashort electron bunches via velocity bunching, rather than through numerical optimization.

Under these conditions, the finite geometry of the gun apertures leads to electron losses, so that not all electrons emitted from the cathode are successfully accelerated and transported out of the RF gun. To investigate this effect, single-particle tracking simulations are performed for electrons emitted at different radial and longitudinal positions on the cathode surface. IMPACT-T results indicate that electrons with initial radial positions greater than approximately 10 mm are intercepted by the inter-cell or gun-exit apertures. Consequently, only electrons emitted within about 10 mm of the cathode center are able to exit the RF gun and propagate downstream (Fig. 2).

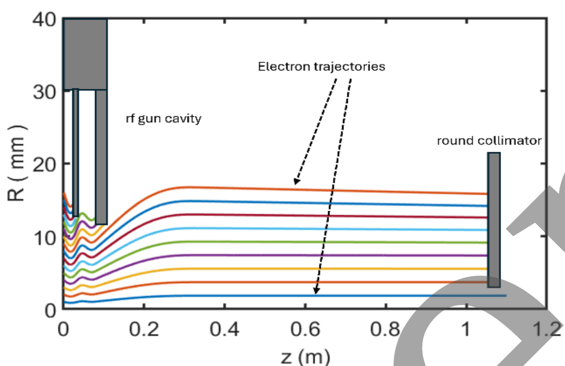

Figure 2: Plots of trajectories of electrons with different initial radial positions on cathode surface.

In practice, the transmitted electrons still exhibit large transverse excursions due to their broad energy spread and the energy-dependent focusing of the solenoid field. As a result, a downstream collimator is required to further suppress off-axis dark current. In this study, a circular collimator was installed 1.05 m downstream of the cathode. Trajectory analysis confirms that the collimator effectively suppresses off-axis dark-current electrons.

Particle-tracking simulations were performed both with and without a collimator featuring a 6 mm-diameter aperture. The results (Fig. 3) show that the fraction of dark-current electrons transmitted through the collimator can be reduced to as low as 9.8%. It should be noted that substantial particle loss already occurs upstream of the collimator due to the RF gun apertures and phase acceptance. This behavior is expected, as only a subset of emitted electrons satisfies the RF phase conditions required for acceleration. In addition, collimators with different aperture diameters ranging from 4 mm to 12 mm were investigated, and particles intercepted by these apertures were accounted for. The results are shown in Fig. 6.

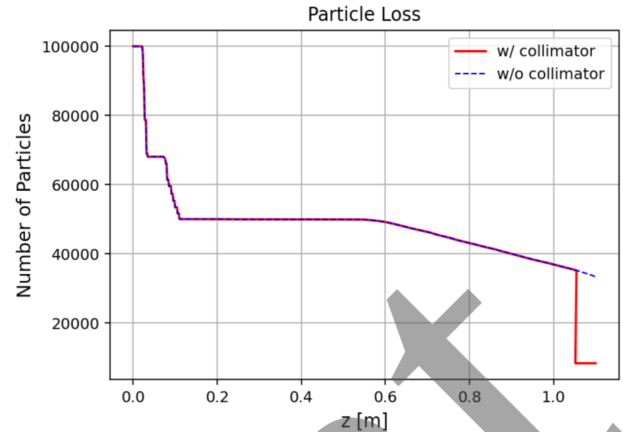

Figure 3: Simulated particle loss in photoinjector with and without a collimator with circular aperture with a diameter of 6 mm.

Even with larger collimator apertures, significant particle loss is observed, demonstrating the effectiveness of the collimation scheme in suppressing dark current.

EXPERIMENT RESULTS AND COMPARISON WITH SIMULATION

To demonstrate the effectiveness of the collimator, a collimation system was installed 1.05 m downstream of the photocathode. At this location, the rms transverse beam size under normal injector operating conditions is sufficiently small to allow the main beam to pass through the collimator aperture without interception. Although this position is not optimized for maximum dark-current suppression, it provides a suitable environment for studying beam–collimator interactions and enables a significant reduction of unwanted dark current.

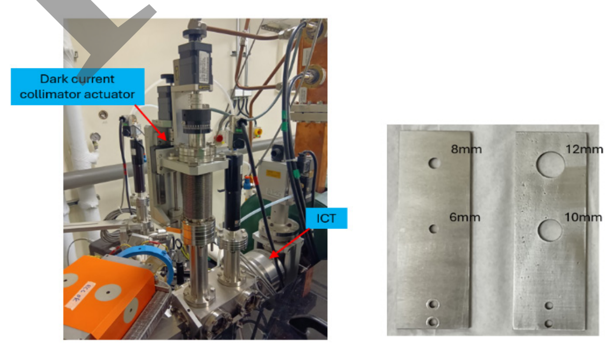

Figure 4: Left: the collimator system and the ICT used for dark current measurements. Right: Molybdenum plates—on the left, plates with aperture diameters of 6 mm and 8 mm; on the right, plates with aperture diameters of 10 mm and 12 mm.

The collimator assembly is fabricated from a solid molybdenum plate containing two circular apertures of different diameters. The plate dimensions—3 mm in thickness, 90 mm in height, and 40 mm in width—were selected to ensure adequate stopping power for both the nominal beam and dark-current electrons under worst-case interception scenarios. The assembly is mounted on a vertically actuated feedthrough, allowing aperture selection during dark-current measurements. A stepper motor drives the actuator to insert the desired aperture into the beam path.

To compare the effectiveness of different aperture sizes in suppressing dark current, two molybdenum collimator plates were fabricated: one with 6 mm and 8 mm apertures, and another with 10 mm and 12 mm apertures, as shown in Fig. 4. Each plate contains two apertures, with sufficient separation between them to ensure that dark current transmitted through one aperture does not pass through the other or interfere with the corresponding measurements.

During the measurements, the RF gun was operated under nominal conditions optimized for the generation of ultrashort electron bunches. The photocathode was illuminated by a Gaussian laser pulse with a full width at half maximum (FWHM) duration of 3 ps, producing an electron bunch with a total charge of 250 pC. Under these operating conditions, the resulting beam energy at the exit of the RF gun was approximately 2.5 MeV. The solenoid magnetic field was set to 1495 G to provide transverse focusing appropriate for velocity bunching and stable beam transport downstream.

The relative transmission of dark current through the collimator was measured as a function of the collimator aperture size and compared with numerical predictions obtained from particle-tracking simulations. For each aperture configuration, charge measurements were performed using an integrated current transformer (ICT). Dark current signals were recorded using a TDS 3034C digital oscilloscope and subsequently processed through a LabVIEW based data acquisition interface. This processing included background subtraction to remove baseline offsets and signal averaging to improve the signal-to-noise ratio. A representative dark current waveform measured by the ICT is shown in Fig. 5.

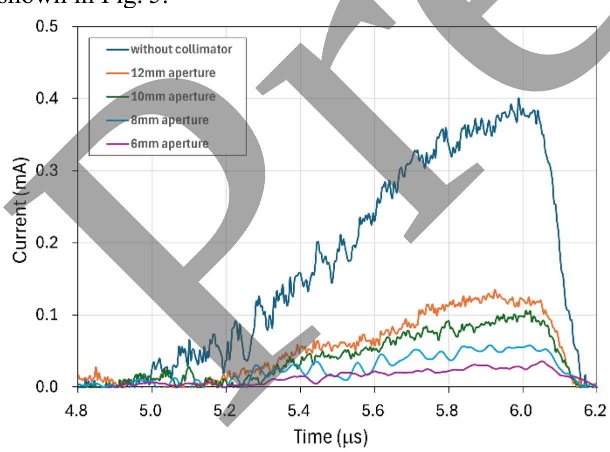

Figure 5: Measured ICT signals downstream RF gun using four apertures with different diameters.

For quantitative comparison, the measured dark current transmission was normalized to the corresponding dark current measured without the collimator in place. When a small aperture diameter of 6 mm was used, the transmitted dark current was reduced to approximately 4.2% of the uncollimated value. In contrast, increasing the aperture diameter to 12 mm resulted in a significantly higher transmission of about 31%, as summarized in Fig. 6. These results demonstrate that the collimator system is highly effective in suppressing unwanted background current and provides a means of protecting downstream accelerator components from excessive dark current interception.

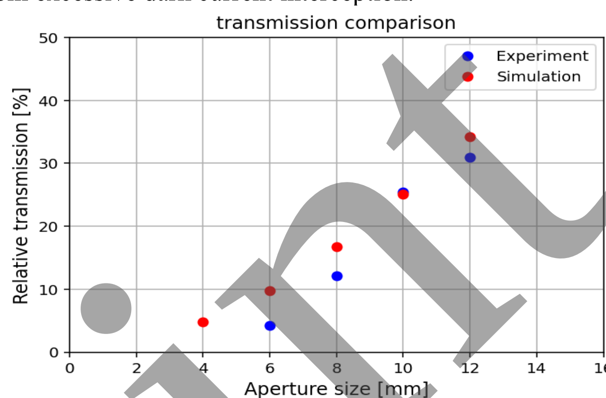

Figure 6: Measured dark current charge downstream the RF gun with different collimator apertures compared with the simulations.

CONCLUSIONS

The effectiveness of the collimator has been systematically evaluated using IMPACT-T simulations incorporating a Fowler–Nordheim field-emission model. The results show that, without mitigation, field-emitted electrons can be accelerated to high energies, posing significant radiation hazards. An upstream collimation system is demonstrated to be an effective and practical means of suppressing high-energy dark current while preserving main-beam quality. These findings support the routine implementation of collimation in high-gradient photoinjectors. At NSRRC, the dark-current collimation system has proven capable of maintaining beam quality and operational safety by intercepting a substantial fraction of dark current through selectable molybdenum apertures. This suppression is critical for protecting downstream undulators, reducing radiation exposure, and improving overall beam performance.

REFERENCES

[1] M. C. Chou *et al.*, "Experimental study of coherent THz sources driven by the NSRRC high brightness photoinjector", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4332-4335.
doi:10.18429/JACoW-IPAC2018-THPMK017

[2] W.K. Lau *et al.*, "Properties of superradiant spontaneous THz undulator radiation by an RF compressed electron beam", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 1877-1880.
doi:10.18429/JACoW-IPAC2023-TUPL055

[3] Y. J. Lin, W.-K. Lau, M.-C. Chou, and W.-Y. Chiang, "Dark current reduction for NSRRC photoinjector system by collimator", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2112-2115.
doi:10.18429/JACoW-IPAC2024-WEPC63