XFEL Accelerator R&D Status Report
RP-214: Basic CW gun research with the PITZ photo injector

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12.09.2025

Scope of the R&D activity

- **Beam dynamics** results relevant for electron sources running in CW (HDC) operation → beam quality at different:
  - gun gradients from 20MV/m to 60MV/m (assumed to be an upper limit for CW SRF gun)
  - types of photocathodes: green vs Cs_2Te (reference case), their emission properties / usability at CW gradients
  - various shapes of photocathode laser pulse (in close connection to ***RP-216: Photo Cathode Laser Shaping***)
  - simulation studies for SRF photo injector combined with **start-to-end XFEL simulations** aiming to figure out a correlation between **beam brightness at the undulator** with beam **performance after the photo injector**

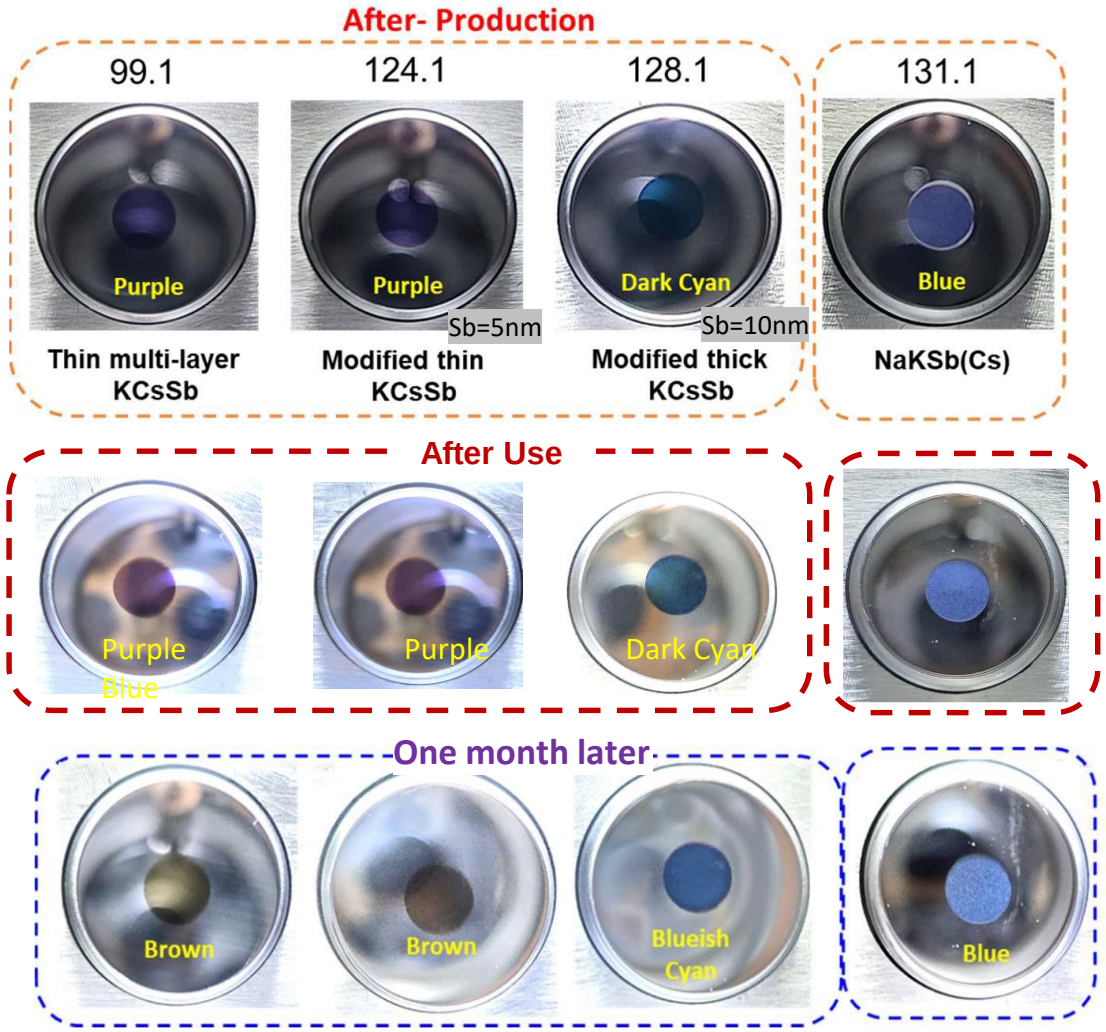
- Studies on cathode material, sensitive to the VIS laser (**Green cathodes**):
  - Green cathode production system at LASA INFN Milano setup to deliver green cathodes to PITZ for tests with RF gun at high gradients.
  - First tests with KCsSb at PITZ : good QE, lower thermal emittance, short response time, but high dark current and short life time
  - Improvements of the green cathode recipe toward high quality green cathodes for CW (HDC) operation
  - *Nanostructured* photocathodes (intended for use in the CW SRF photogun) are also planned to be tested under high-gradient, long-RF-pulse conditions → collaboration established

Achievements in 2024: Post-Usage Analysis of the Second Batch of Green Cathodes

- 4 cathodes were produced:
  - 3 KCsSb (modified recipes) → QE ~ 8-9.6%@514nm
  - 1 NaKSb(Cs) → QE ~ 0.006%@514nm

- All of these cathodes were successfully transported and tested in the PITZ RF gun
  - **No major vacuum events** occurred during operation
  - **Dark current** remained *stable* over time but was **higher** than that of the Cs_2Te cathode
  - Measured **thermal emittance** was approximately **×2 higher** than the first batch and theoretical expectations; the reason is unknown (partially measurement discrepancy)
  - **QE degradation** (< 1%) in ~3 days of operation
  - No visible color change is observed **after use**

- **One month after** the initial spectral analysis, KCsSb cathodes showed color change and **QE drop**, while NaKSb(Cs) cathode remained unchanged



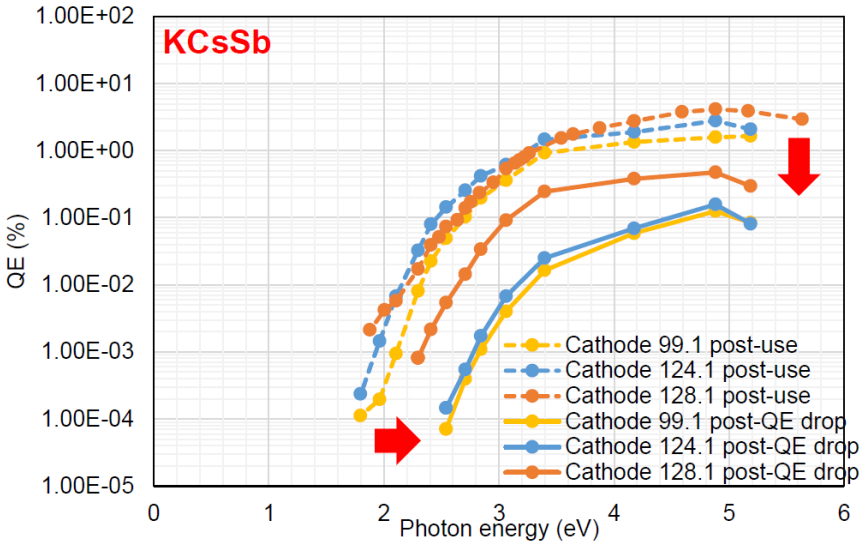
Achievements in 2024: Green cathodes, post QE-drop investigations

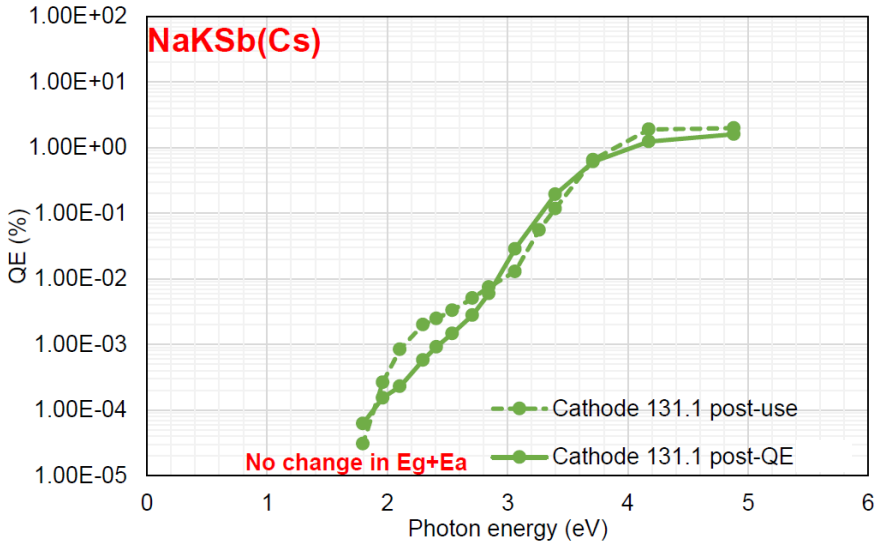
QE drop one month after the initial spectral analysis:

- Eg + Ea increased for all three KCsSb cathodes (from 1.9 eV to ~2.54 eV), while there was no change for NaKSb (Cs)

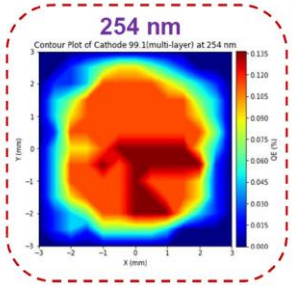
- RGA analysis → no major contamination detected
  ➔ No conclusive evidence from RGA to explain the observed QE drop in KCsSb cathodes

- QE maps (measured for all four cathodes at different wavelengths post-QE drop) showed reasonable uniformity.

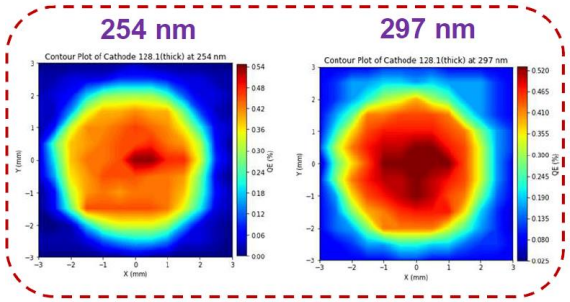




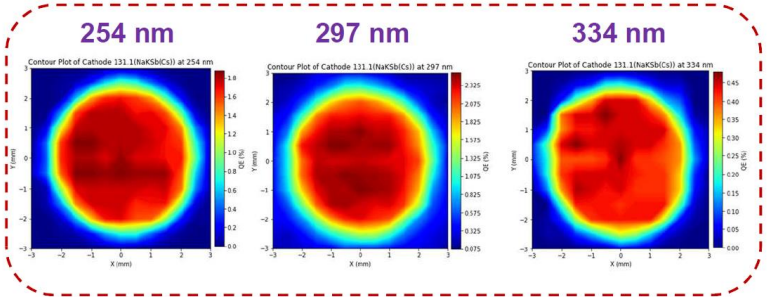
Cathode 99.1 (Thin multi-layer)



Cathode 128.1 (Modified thick)



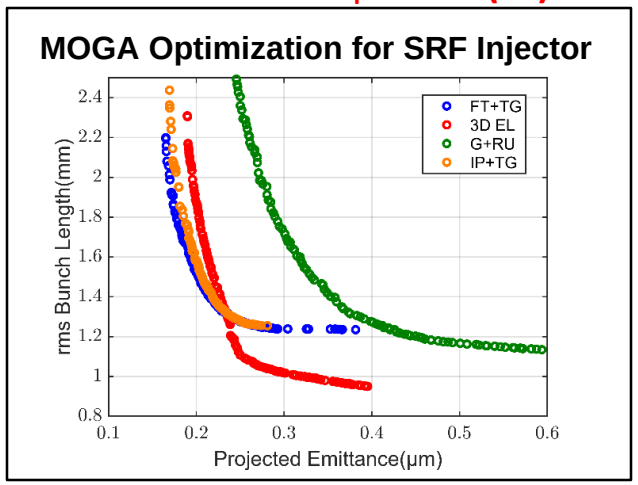
Cathode 131.1 (NaKSb(Cs))

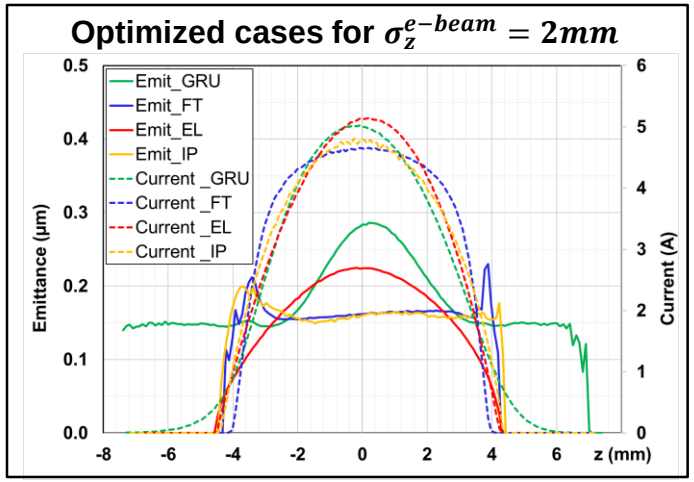


PhD Thesis “Development of Multi-Alkali Antimonide Photocathodes for High-Brightness RF Photoinjectors” was defended by Sandeep Mohanty at University of Hamburg, PUBDB-2024-07054

Achievements in the past year: BD simulations for SRF Photoinjector → Benchmarking at PITZ

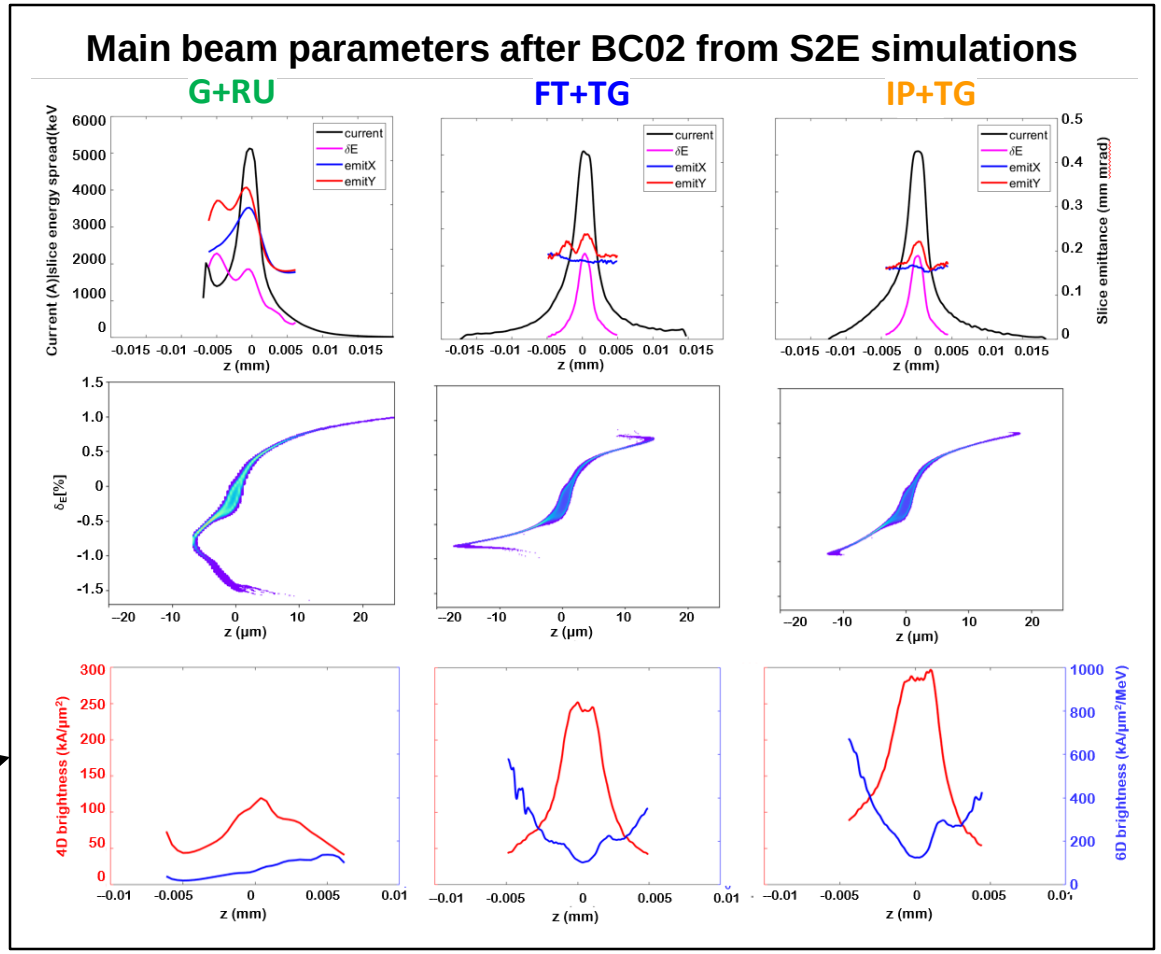
- Comparison of photocathode laser pulse profiles:
  - Temporal: Gaussian **(G)**, flattop **(FT)**, inverted parabolic **(IP)**
  - Transverse: radially uniform **(RU)**, truncated Gaussian **(TG)**
  - 3D: ellipsoidal **(EL)**





- Optimized Photoinjector (100pC from SRF gun + A1)

→ further track (S2E, incl BCs) to undulator



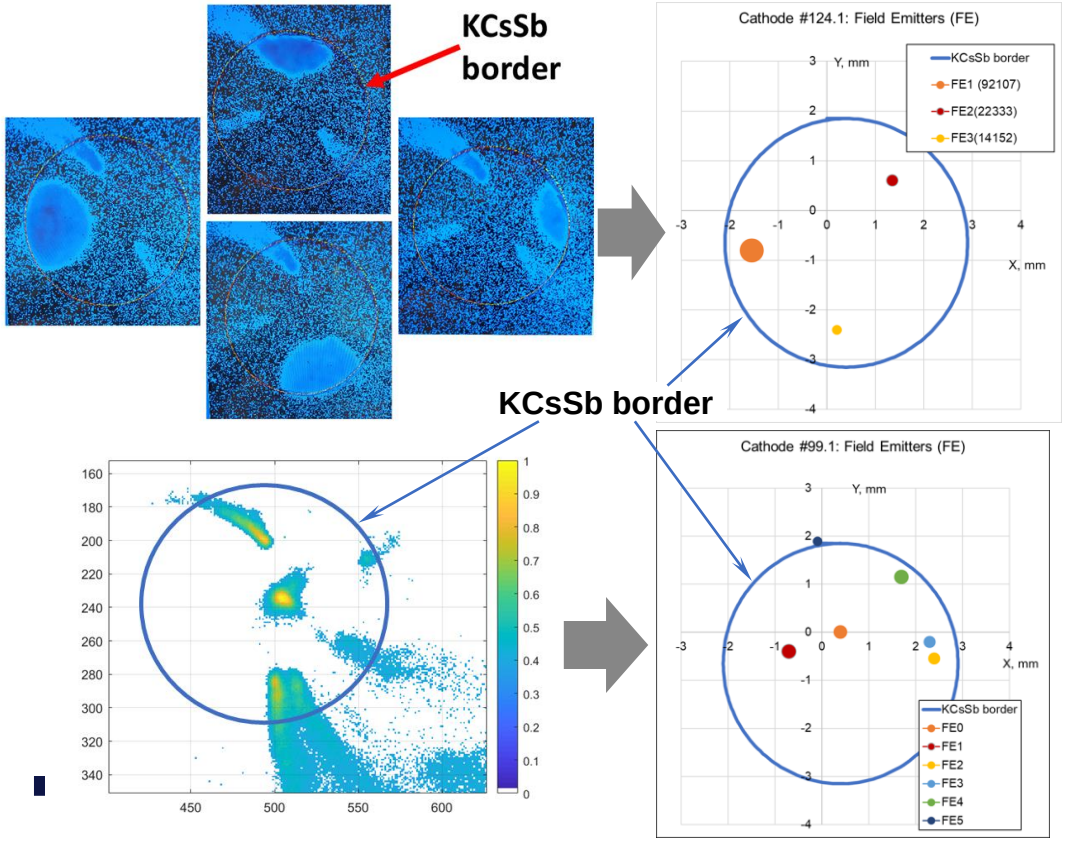
➔Laser pulses with **IP+TG** are promising, brightness $B_{4D,6D}$:

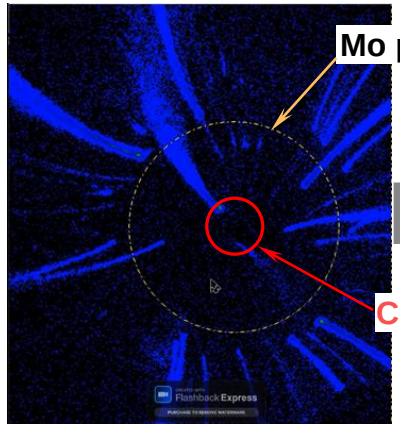
- from the injector: comparable to **EL**
- after BC02 (S2E simulations): better as compared to **FT**

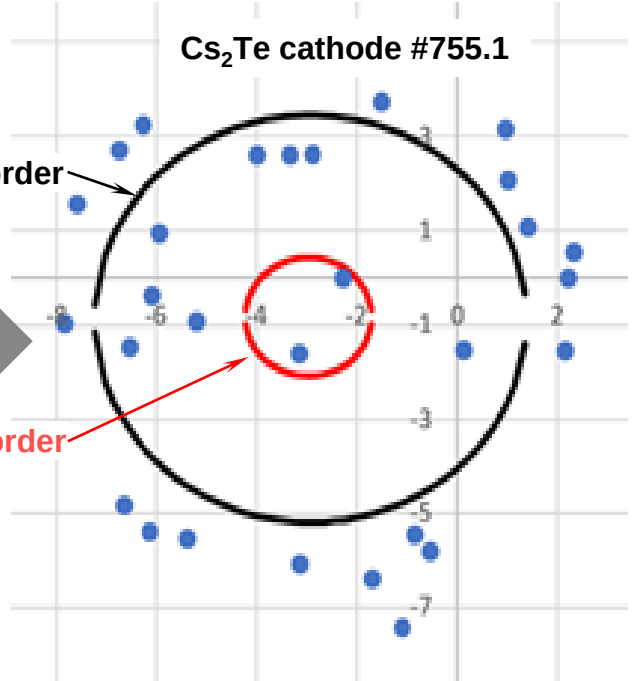
✓ With less technically challenges to produce these shapes

Achievements in the past year: Dark current imaging at PITZ → for SRF Gun

- **Method for Localizing Field Emitters (FE Mapping) at the Cathode Plane of the RF Photogun**
  Based on dark current imaging; developed and tested at PITZ for both KCsSb and Cs_2Te photocathodes
  - Use photoelectron beam with controlled laser spot positioning (via virtual cathode camera)
  - Identify borders of active photocathode area using a large laser spot
  - Localize field emitters with a small laser spot → apply transfer matrix







➔The method is anticipated to be applicable to the SRF CW gun (Ts4i)

HELMHOLTZ DESY

Deviations from plan

- PITZ Timeline Update (2024–2025) → Gun5 for XFEL is the highest priority !!!:
  - Gun5.1 was dismounted for refurbishment, including the cathode hole and contact spring → *not for use at XFEL*
  - Gun5.2 since January 2025 in operation at PITZ (conditioning + characterization with e-beam) → XFEL Sept.2025
  - Gun5.3, now FALCO (single-side power coupler) → PITZ in October 2025+ *symmetric power coupler* (once ready), with conditioning and characterization planned to start at the **end of 2025**
  - Several **major technical failures** significantly disrupted the characterization schedule:
    - ***Water leak in the bucking solenoid***, requiring its replacement along with one RF window. This necessitated opening the gun vacuum system, leading to a ~3-week shutdown and a subsequent re-conditioning period
    - Campus-wide ***power outage*** at DESY Zeuthen on 21.04.2025, resulted in ~2.5 weeks of down-time
    - ***Failure*** of the ***RF1*** (booster) klystron modulator capacitor bank, causing an estimated ~4-week delay.

- **2nd batch green cathodes** was tested with the Gun5.1 at PITZ in summer 2024, still not expected performance, post-use analysis done. Since January 2025 Gun5.2 in operation at PITZ → risk of contamination → no further green cathode tests ➔ ***all milestones with green cathodes test at PITZ are not achievable (prioritization)***

- Additional studies with Gun5.2 using flattop laser pulses from NEPAL-P were carried out at 60 MV/m. Tests at ***lower gradients*** were postponed due to limited operation time and the priority given to **long-term high-gradient studies of Gun5.2**. It is not clear whether this milestone can be reached by the end of 2025 by using Gun5.3.

Timeline of this R&D activity

Proposed Date	Milestone Description	Updated Date
~~Q4/2023~~ **Q4/2025**	**Beam characterization and emission properties at 60 MV/m (~upper limit for CW SC gun) with ellipsoidal and other advanced laser pulse shapes and Cs2Te cathodes** Some further studies done with Gun5.2 and flattop laser pulses from NEPAL-P	**partially done Q3/2021** **Q3/2025**
~~Q4/2023~~ **Q4/2025**	Beam characterization and emission study at realistic NC CW gun gradients (probably in the range **20-30 MV/m**) with **flat-top** laser pulse shapes and **Cs2Te** cathodes Due to the limited operating time of Gun5.2, we did not have time to perform these studies as the characterization at 60MV/m had higher priority for the XFEL operation. It is not clear whether this can be reached by the end of 2025.	partially done Q3/2021
~~Q1/2023*~~ **Q1/2024***	First beam characterization and emission study at realistic NC CW gun gradients (probably in the range **20-30 MV/m**) with **flat-top** laser pulse shapes and **green** cathodes	partially done Q3/2024
~~Q2/2023*~~ **Q4/2023***	Further development of deposition method for the production of green cathodes allows to reach longer lifetime and lower vacuum sensitivity. Improvements are observed but are not sufficient yet.	partially done Q4/2022 and Q3/2024
~~Q2/2023*~~ **Q4/2023***	Beam characterization and emission study at **~40 MV/m** with **Cs2Te** or/and **green** cathodes	Partially done Q3/2024
~~Q2/2024~~ **Q4/2025***	Robustness of green cathodes is increased so that they can be operated at 60 MV/m First beam characterization and emission study at 60 MV/m with flat-top laser pulse shapes and green cathodes Reproducible production of high-quality green cathodes for continuous operation Beam characterization and emission study at 60 MV/m with ellipsoidal laser pulse shapes and green cathodes	highly unlikely to be achievable

Risks to R&D Project

- Green cathode test:
  - Due to the prioritization of Gun5 (Gun5.2 and Gun5.3 for XFEL), operation with green cathodes is not foreseen before the end of 2025 (last 4 month of the project)

- Gun5 operation at PITZ:
  - Gun5.1 was dismounted for refurbishment (incl. the cathode hole and contact spring), currently not for use
  - Gun5.2 is on the way to XFEL
  - Gun5.3, after pre-conditioning at FALCO with a single-side power coupler, is expected to be delivered to PITZ (October 2025), will be equipped then with a symmetric power coupler, with conditioning and characterization planned to start in Fall/Winter 2025.

- Other risks:
  - Hardware failures (e.g., RF systems; three major technical failures already in 2025)
  - Conflicts with other tasks

Outlook / Summary

- XFEL Accelerator R&D activities RP-214: “Basic CW gun research with the PITZ photo injector” in 2025:
  - Beam characterization and emission studies with flattop laser pulses at 60 MV/m in Gun5.2
  - Green cathode tests: performance still below expectations; post-use analysis ongoing
  - Collaboration on nanostructured photocathodes (for CW SRF photogun) established
  - Dark current imaging (FE mapping) procedure developed and tests → to be applied at CW SRF gun (Ts4i)
- Plan for a follow-up proposal:
  - Specific studies for HDC (Scenario 3 / Gun5)
  - Developments and testing of components (e.g., nanostructured cathodes) for CW XFEL operation
- **List of publications:**
  - S. Mohanty, “Development of Multi-Alkali Antimonide Photocathodes for High-Brightness RF Photoinjectors”, PhD Thesis, University of Hamburg, PUBDB-2024-07054
  - S. Zeeshan et al., "Beam dynamics optimization in high-brightness Photo Injector with various photocathode laser pulse shapes", in Proc. IPAC'25, Taipei, Taiwan, Jun. 2025, pp. 1454-1457. doi:10.18429/JACoW-IPAC25-TUPS019