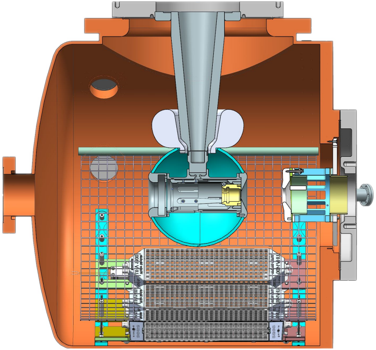
LDRD for a high-current polarized-beam photogun

Max Bruker
Center for Injectors and Sources

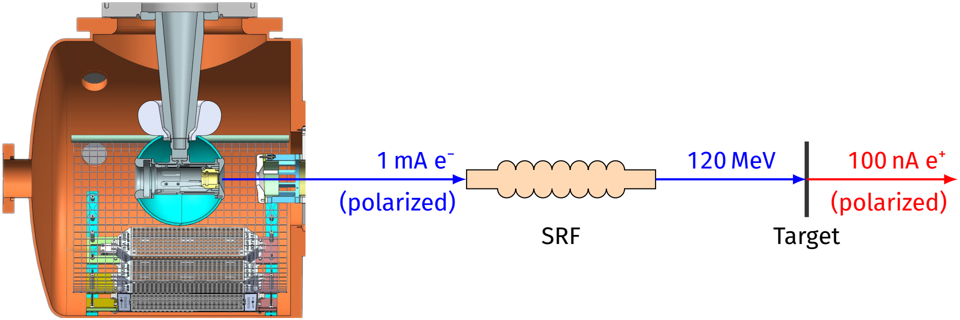
Positron Working Group meeting
March 25, 2025

The research described in this presentation was conducted under the Laboratory Directed Research and Development Program at Thomas Jefferson National Accelerator Facility for the U.S. Department of Energy.



Example of a state-of-the-art polarized photogun:
the 200 kV CEBAF gun (“R30”)

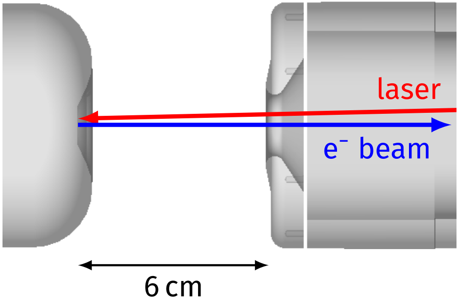
Generating the electron beam for the positron injector



- High beam current determined by low conversion efficiency
- Electron beam must be polarized to make polarized positrons

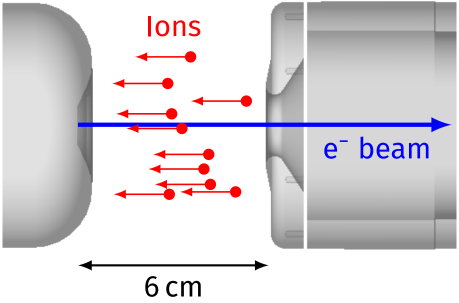
Gun requirements

- Laser-driven photogun (780 nm) with GaAs-based photocathode
- Technology is mature, design can be based on existing guns (e.g., CEBAF)
- Most required parameters are not challenging:
  - bunch charge: 4 pC (1 mA at 250 MHz)
  - bias voltage: lower limit given by subsequent RF structures, TBD
    - 200 kV routinely achieved, can do more if needed
  - spin polarization > 80 % is standard, not current-dependent



Dominant limitation of photocathode lifetime: ion back-bombardment

- Electron beam ionizes residual gas within accelerating gap
- Ions are accelerated toward the photocathode, rate ∝ current
- Ions striking photocathode surface locally degrade its quantum efficiency (QE)
- Accept 10× decrease between activations: ≈ exp(−2)
- CEBAF: 1/e lifetime 300 C
  ⇒ 2 lifetimes ≈ 7 days at 1 mA

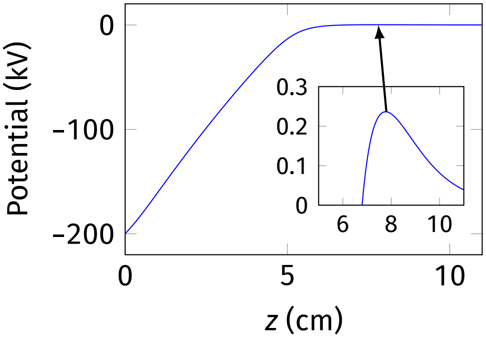


Requirement for unprecedented lifetime of high-polarization photocathodes (1/e lifetime > 1000 C would give ≈ 23 days uptime at 1 mA)

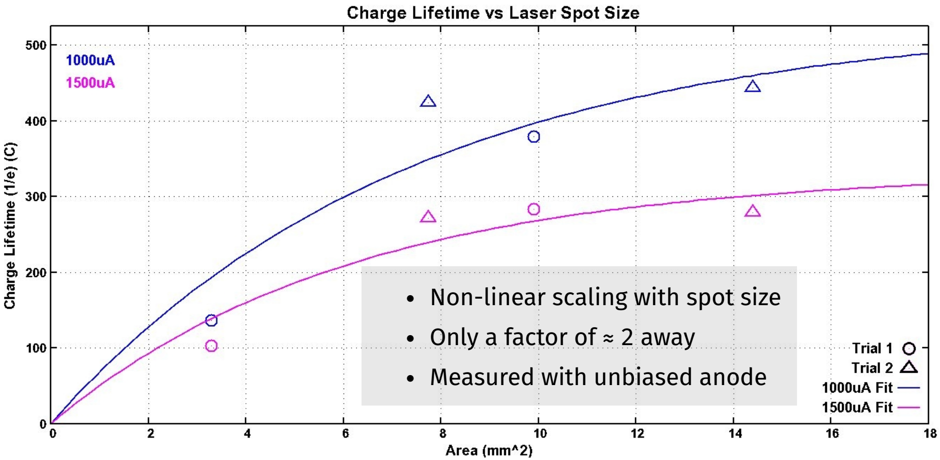
How to increase the charge lifetime

- Improve vacuum: already ≈ XHV
- Increase voltage (ionization cross-section): unclear trade-off
- Make the photocathode less sensitive: being worked on independently
- If we have to accept the remaining ions, can we displace/dilute the damage?
  - Use as much photocathode area as possible for emission
  - Deflect electrons and/or ions to displace damage area

- Apply positive bias to anode for a potential barrier to reflect ions from downstream: already standard



CEBAF measurement of lifetime vs. laser-spot size (2017)



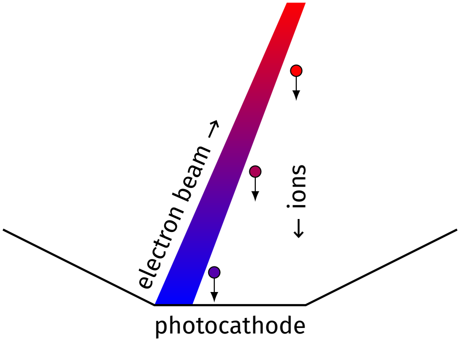
- Non-linear scaling with spot size
- Only a factor of ≈ 2 away
- Measured with unbiased anode

J. Grames et al., "Milliampere Beam Studies using High Polarization Photocathodes at the CEBAF Photoinjector," Proceedings of XVII International Workshop on Polarized Sources, Targets & Polarimetry — PoS(PSTP2017), vol. 324, 2018, p. 014

Jefferson Lab

A closer look at the dynamics

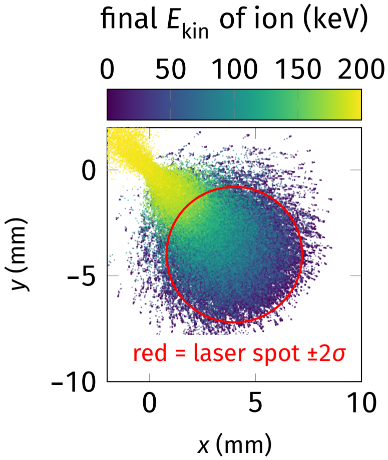
- Electron beam envelope determines starting position of ions
- Low energy: close to photocathode, damage area ≈ emission area
- High energy: far away from photocathode, damage area depends on optics…
  - Deflect electron beam away from emission area ⇒ shift ion origin
  - Ions close to the anode are also subject to its focusing field
- Simulate in detail



Beam trajectory in gap determines energy distribution of ions incident on emission area

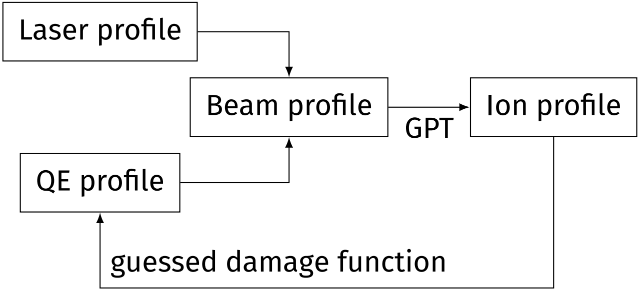
Simulating ion damage in photoguns

- Need electrostatic field map (CST)
- Ions are created inside electron beam depending on envelope and energy
  ⇒ simulate electron dynamics with General Particle Tracer (GPT)
- Extend GPT with IONATOR to get ions and track to photocathode in the same model
- Problem: QE degradation depends on ion energy in an unknown way
  (likely: more energy ≈ worse)

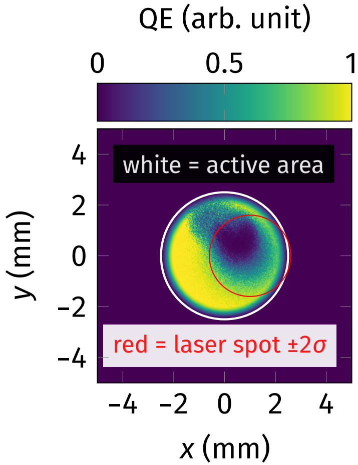


Simulated ion distribution hitting the photocathode (example gun)

Simulating lifetime

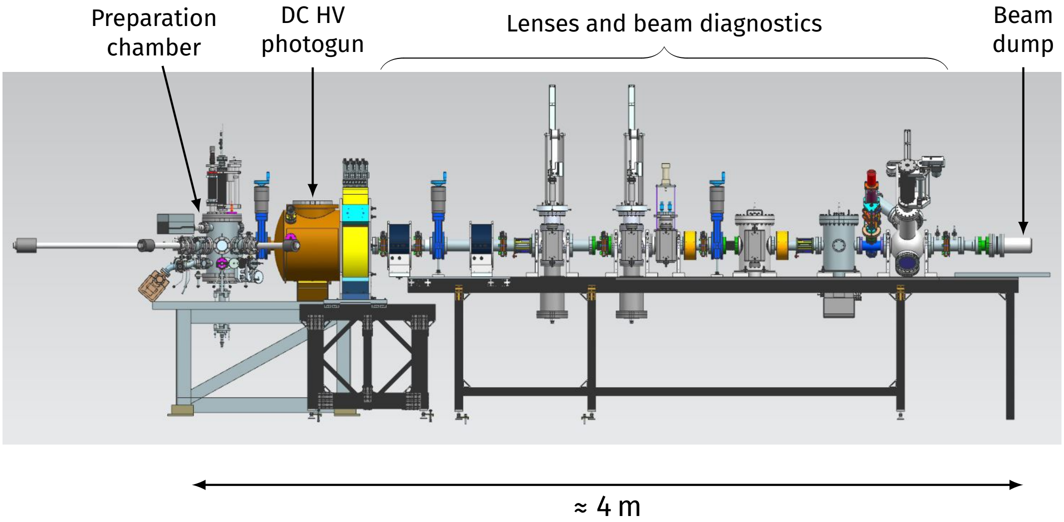


- Most of the dynamics can be simulated from first principles
- Reasonable guess of damage function should allow for qualitative comparisons

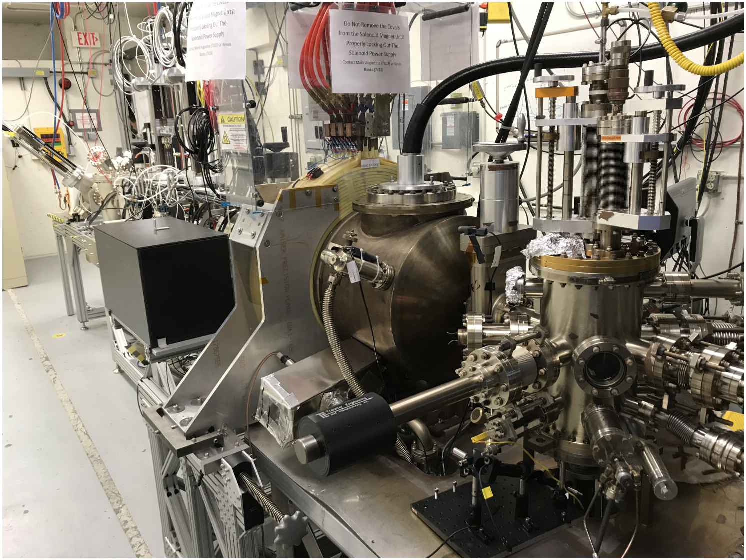


Example simulation, after 50 time steps

Lifetime measurements at the Gun Test Stand (GTS) in the LERF building



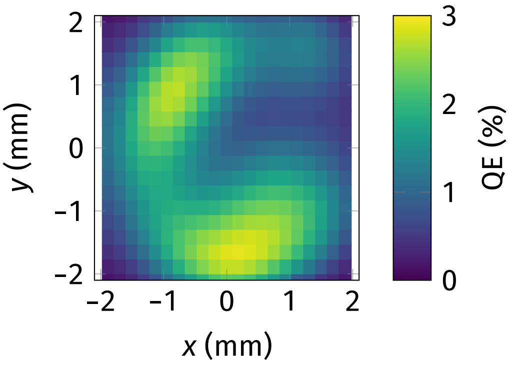
GTS photo



Jefferson Lab

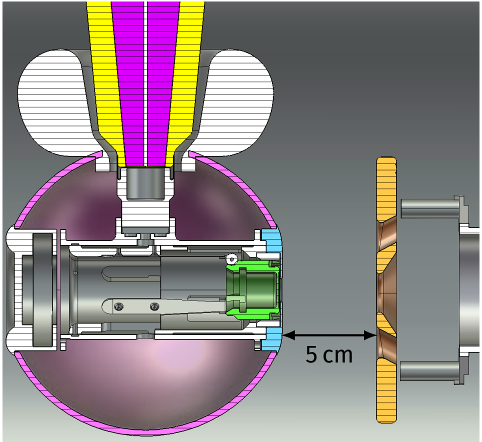
QE damage measurements

- No direct way to measure the ion distribution on the photocathode
- QE can be measured as a function of position
  - Caveat: convolution with laser profile ⇒ minimize spot size for measurement
- Extract a known amount of charge with a given laser-spot size, then compare measured and simulated QE distribution to calibrate simulation model
- Systematic studies at GTS to happen this year

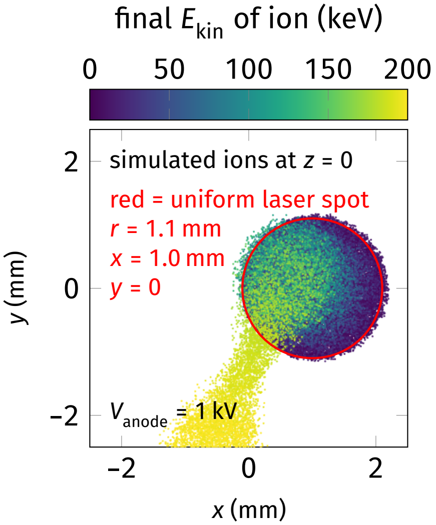


Example of a QE scan from UITF, showing ion damage on bulk GaAs

Status of GTS simulations with the as-built gun

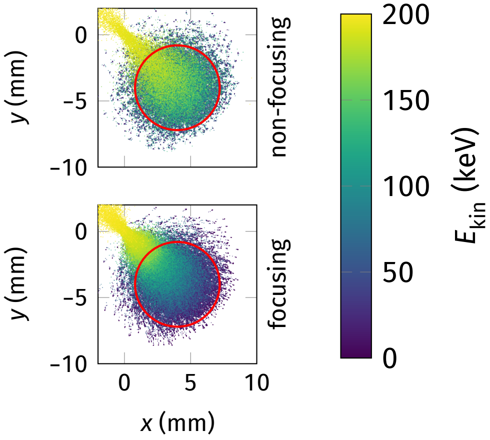


CST model by G. Palacios-Serrano



Cathode focusing

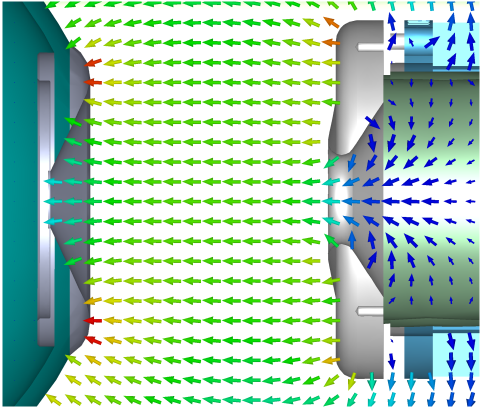
- Most guns focus the beam to manage its envelope
- GTS gun is ≈ non-focusing to maximize surface field
  ⇒ good test case for comparison
- Prototype: focal length ≈ gap length
    - Large deflection of off-center beam while centered in anode
      ⇒ displaced ions
    - Correct for deflection downstream
    - Large divergence needs focusing
    - Low-aberration gun optics for clean off-center emission



Simulated ion distributions for non-focusing (top) and focusing (bottom) example guns

Design of gun electrodes to enhance lifetime

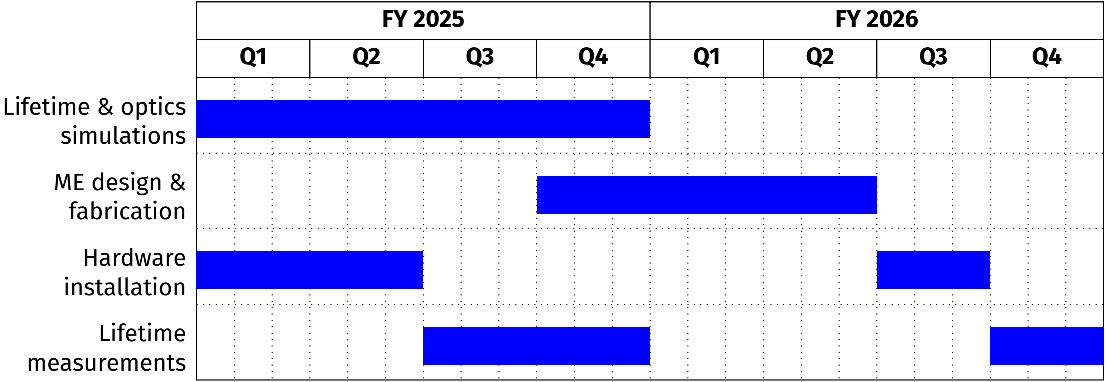
- Standard focusing cathode electrodes are ≈ conical
- Non-ideal transition to flat photocathode & electrode size constraints (surface field) cause aberrations
  ⇒ large emittance for off-center emission with large spot size
- Lift constraints later, optimize field geometry first (cost & project scope)
- Unusual paradigm: engineer the field for low ion damage, not primarily electron beam dynamics



Example of a strongly focusing gun: R30-3 electrode geometry and field distribution

Examples of fabricated electrode assemblies

Expected project time line



- Objective: predictable, enhanced charge lifetime for high-current operation
- GTS about to start up, expecting beam results this year

Backup: $Ce^{+}BAF$ positron injector layout