# Development of High-average-current RF Injectors


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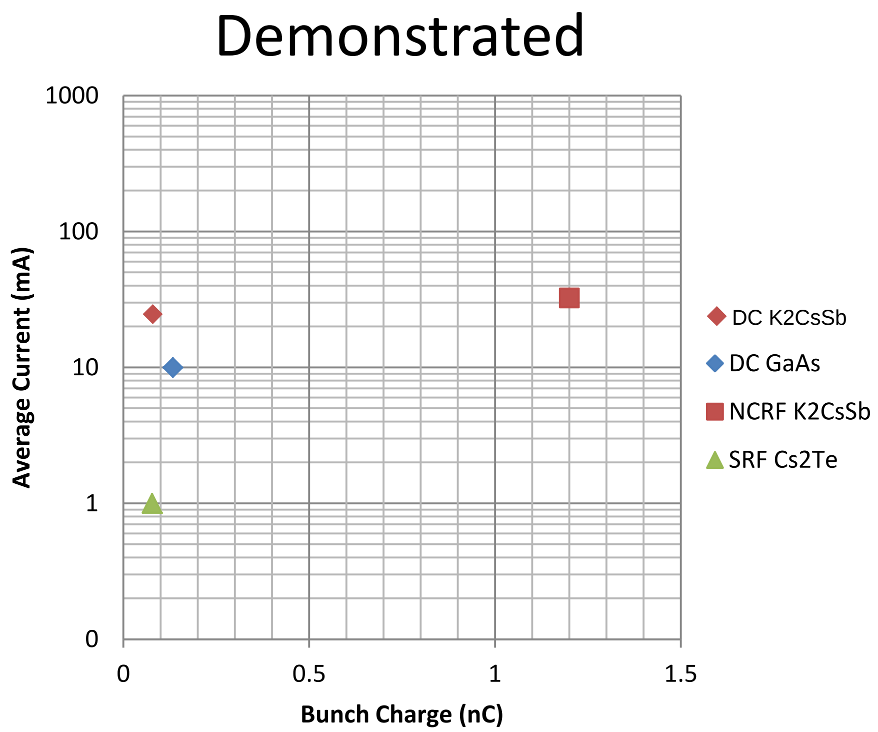
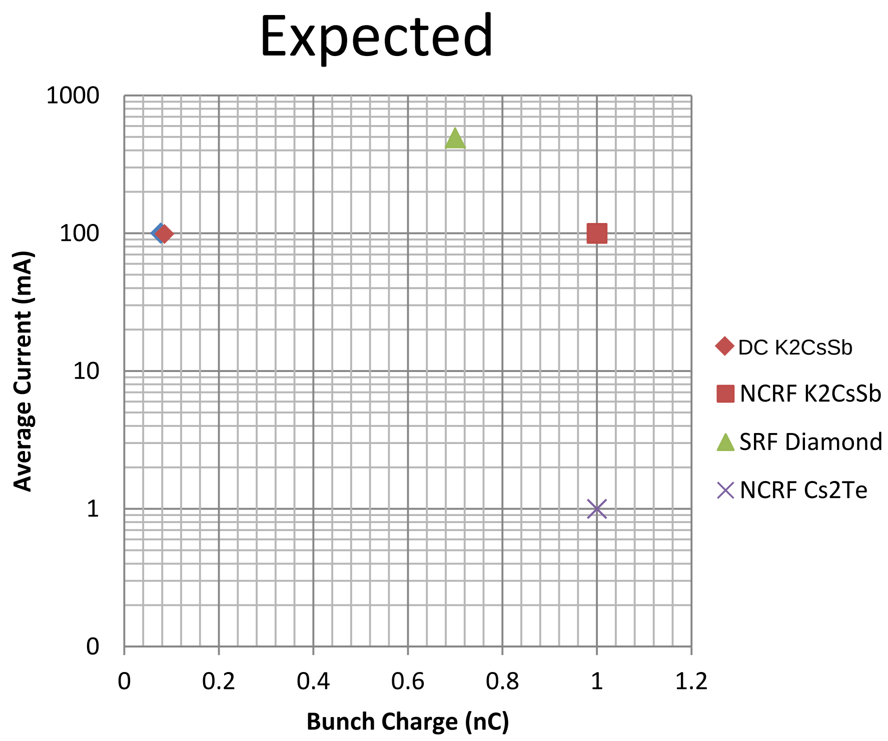
# Electron Beam Requirements

| | |
|---|---|
| • Bunch charge | 0.1 – 1 nC |
| • Repetition rate | <1 GHz |
| • High duty factor | >10% |
| • Peak cathode gradient | 10 – 25 MV/m |
| • Beam energy | >1 MeV |
| • Normalized rms emittance | 0.1 – 3 μm |
| • Bunch length | 1 – 10 ps |
| • Energy spread | <0.1% |

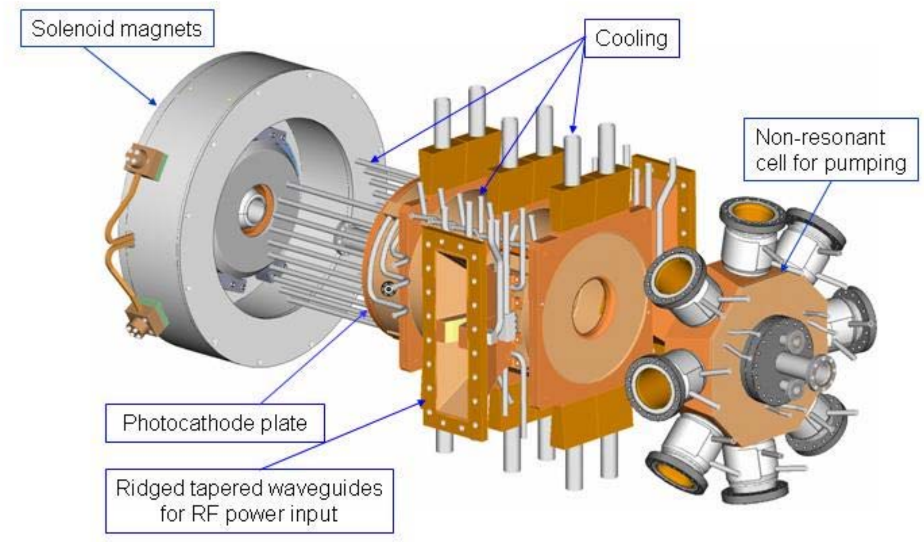
# Demonstrated and Expected Performance

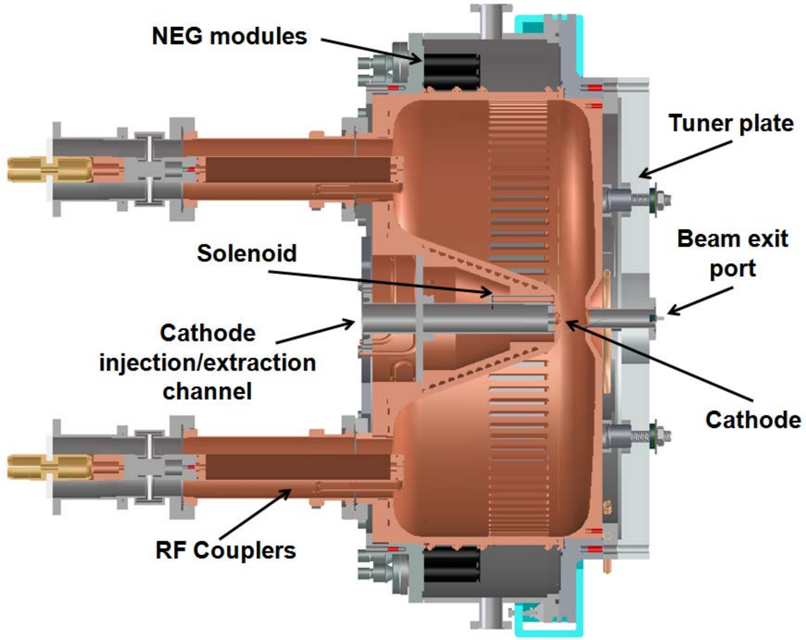



No injector thus far has demonstrated more than 32 mA.

# CW Normal-Conducting RF Injectors

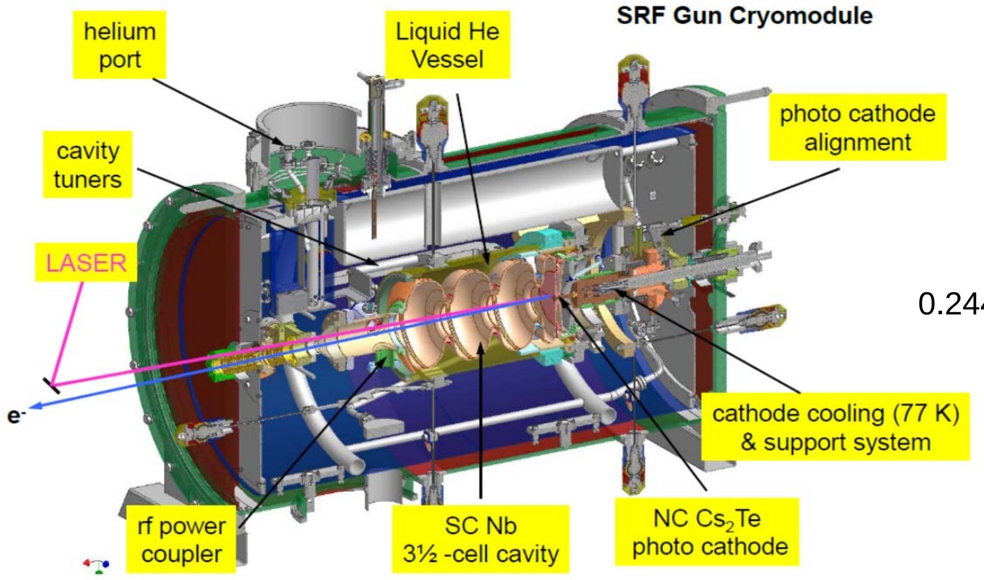


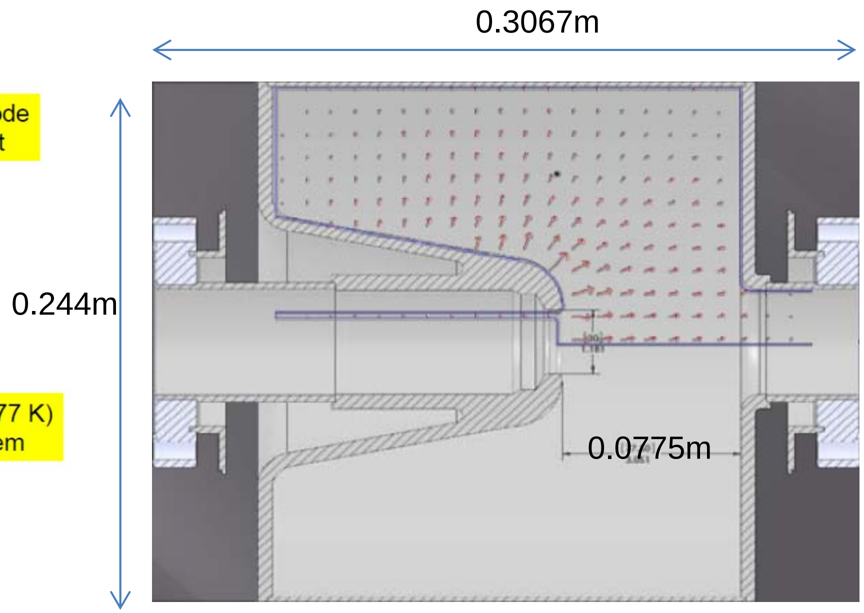




**LANL/AES 700 MHz Gun**
**2.5-cell Full-wave**

**LBNL 187 MHz Gun**
**Single-cell Quarter-wave**

# CW Superconducting RF Injectors




**Rossendorf 1300 MHz Gun**
**3.5-cell Full-wave**

**NPS/Niowave 500 MHz Gun**
**Single-cell Quarter-wave**

# Key Design Considerations

- Emittance Compensation
  – Solenoid: Demonstrated good emittance
  – RF focusing: Insufficient but provides extra focusing
- Cathode gradient
  – Too high: Field emission, ohmic losses (NCRF)
  – Too low: Space charge limited
- Photocathodes & lasers
  – Semiconductor: High QE, short lifetime; visible light
  – Metal: Low QE, long lifetime; UV light

# Emittance Compensation

Envelope equation

$$\sigma'' + \sigma' \frac{\gamma'}{\beta^2\gamma} + K_r\sigma - \frac{\kappa}{\beta^3\gamma^3\sigma} - \frac{\varepsilon_n^2}{\beta^2\gamma^2\sigma^3} + \frac{e}{\gamma mc^2}\left(\upsilon_z B_\theta - E_r\right) = 0$$

Acceleration damping

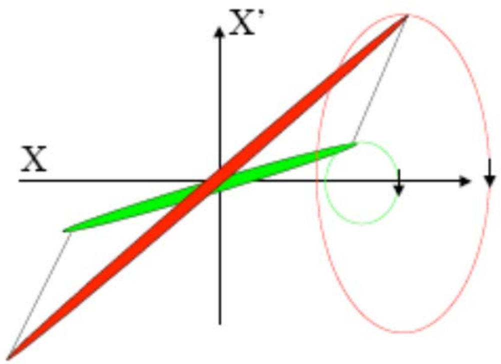
Solenoid focusing

Space charge

rms emittance

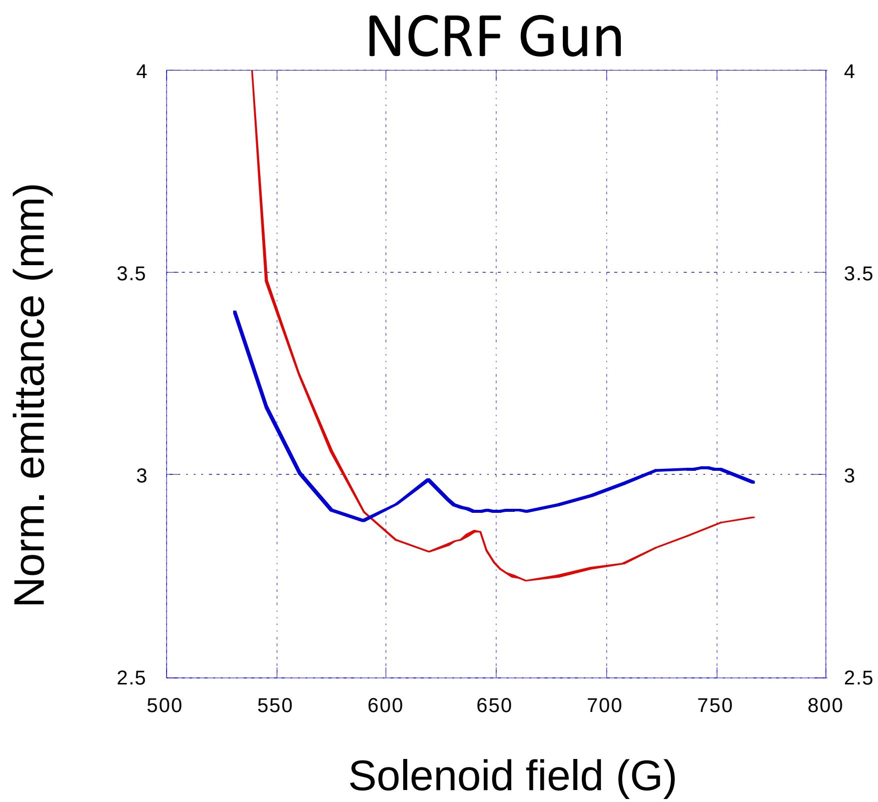
RF focusing & defocusing

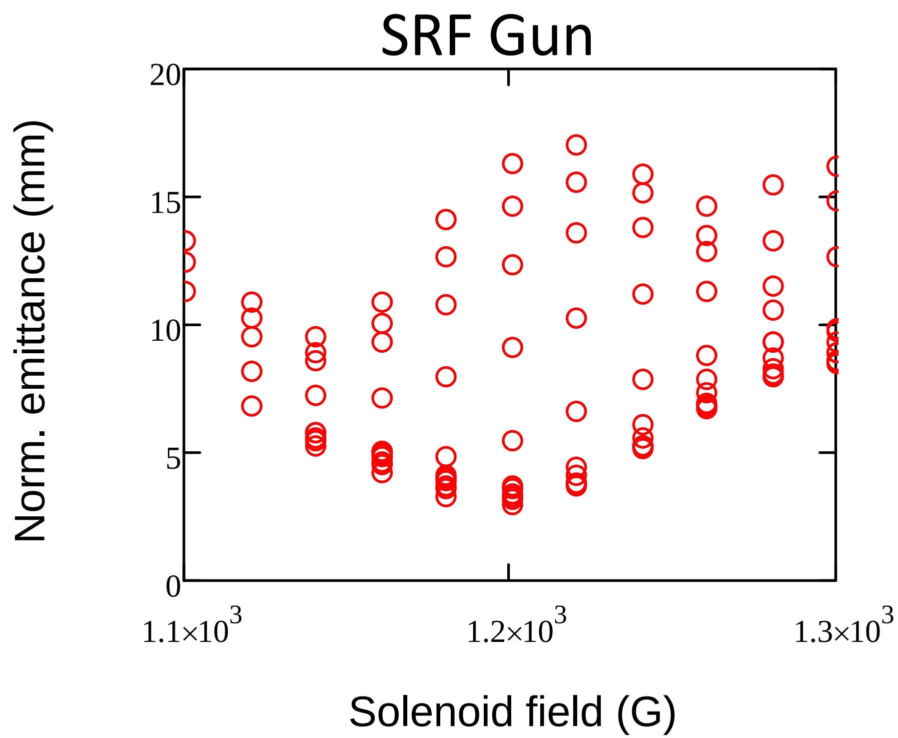
Invariant envelope $\sigma_{inv} = \frac{2}{\gamma'}\sqrt{\frac{I}{3\gamma_0 I_A}}$




Solenoid and RF magnetic field focusing (at small injection phase) can limit both space charge and RF induced emittance growth.

# Emittance Compensation in NCRF & SRF Guns




PARMELA simulations show the feasibility of generating nC bunch charge beams with normalized rms emittance of 2–3 μm

# Field Emission Consideration

- Cathode gradient
  - High cathode gradients lead to high dark current
- Photocathodes
  - Cathodes with low work function have high dark current
  - Rough surfaces have high dark current

Fowler-Nordheim Equation

$$J = A\frac{(\beta E)^2}{\Phi}10^{\frac{4.52}{\sqrt{\Phi}}}\exp\left[\frac{-B\Phi^{\frac{3}{2}}}{\beta E}\right]$$

$A = 1.54 \times 10^{-6}$ A eV/V$^2$

$B = 6.53 \times 10^{3}$ MV/m eV$^{-1.5}$

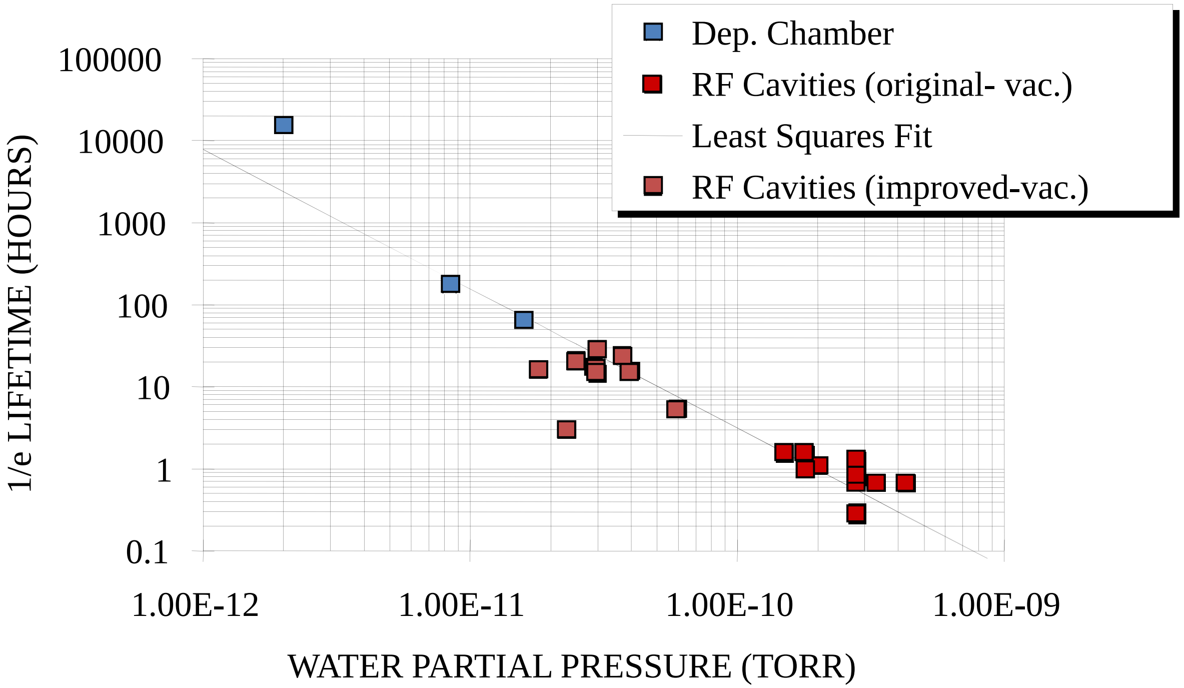
$\Phi$ → Work function

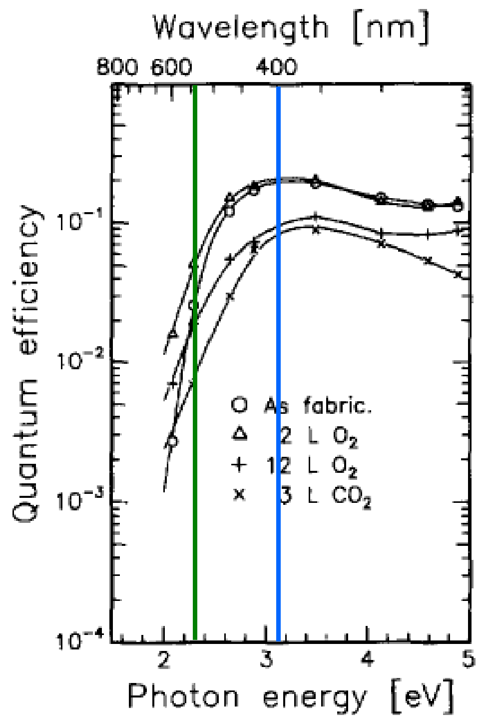
$\beta$ → Field enhancement

# $CsK_2Sb$ Photocathode

QE at 532 nm = 5%
1/e Lifetime with $10^{-10}$ torr $H_2O$ = 3 h
1/e Lifetime with $3 \times 10^{-11}$ torr $H_2O$ = 20 h

QE improves at higher photon energy (shorter $\lambda$)



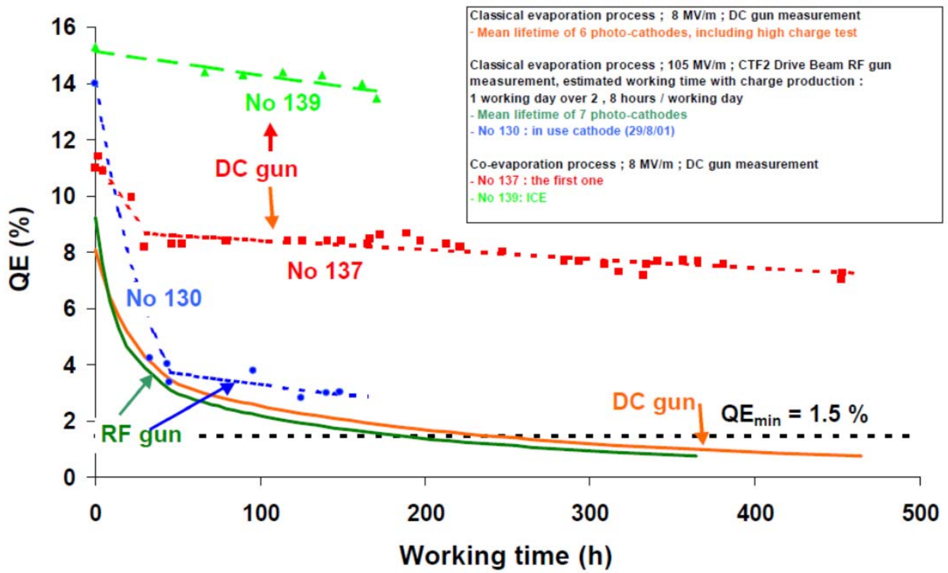




*Courtesy of Dave Dowell ($CsK_2Sb$ data with the Boeing injector)*

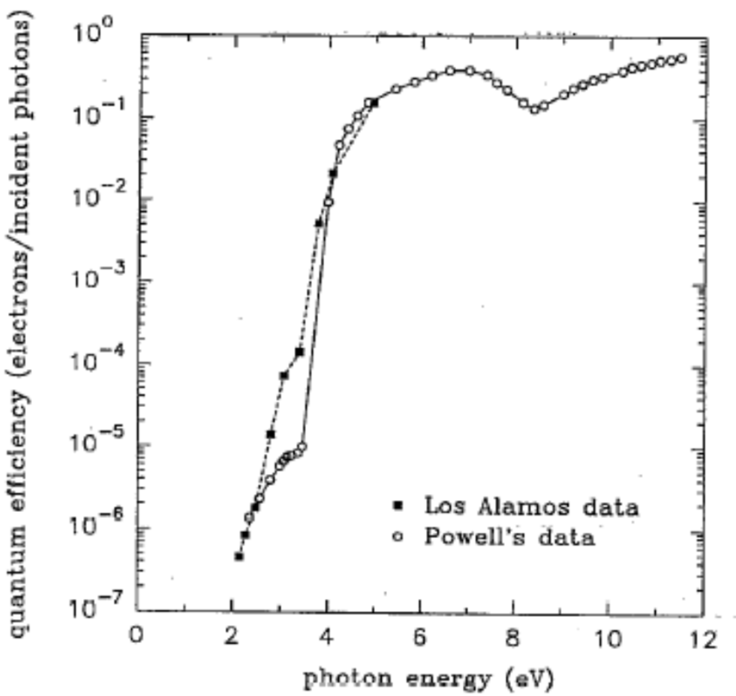
# $Cs_2Te$ Photocathode

First QE = 14%
First 1/e Lifetime = 30 h
Second QE = 4%
Second 1/e Lifetime = 300 h

$Cs_2Te$ require high energy photons ($\lambda$ < 300 nm)




*Courtesy of Suberluqc ($Cs_2Te$ data with the CLIC injector)*




*S. Kong et al., J. Appl. Phys. 77(11) 6031 (1995)*

# Conclusions

- CW injectors operate at much lower gradients and frequencies than low-duty, pulsed injectors.
- Emittance compensation is necessary to achieve high-brightness electron beams at low gradients.
- Field emission (dark current) is an important design consideration for high-duty injectors.
- The choice of photocathodes affects the maximum cathode gradient, complexity of the drive laser, and injector operation time.