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# Cathodes for Multi-Pulse Injectors

**Mark Hess**  
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# Overview

- Explosive Field-Emitter Cathodes
  - Velvet, Carbon Fiber
- Thermionic Cathodes
  - Dispenser Cathodes
- Photocathodes

# Explosive Field-Emitter Cathodes

## Low Voltage Perveance (Velvet)

$$P = \left( \frac{4\pi\epsilon_0}{9} \right) \sqrt{\frac{2e}{m}} \left( \frac{r}{d} \right)^2$$

$$= (7.3 \times 10^{-6}) \left( \frac{r}{d} \right)^2 (A/V^{3/2})$$

## Gas Column Expansion Velocity

$$v_f = 0.1 - 1 \text{ cm}/\mu\text{s}$$

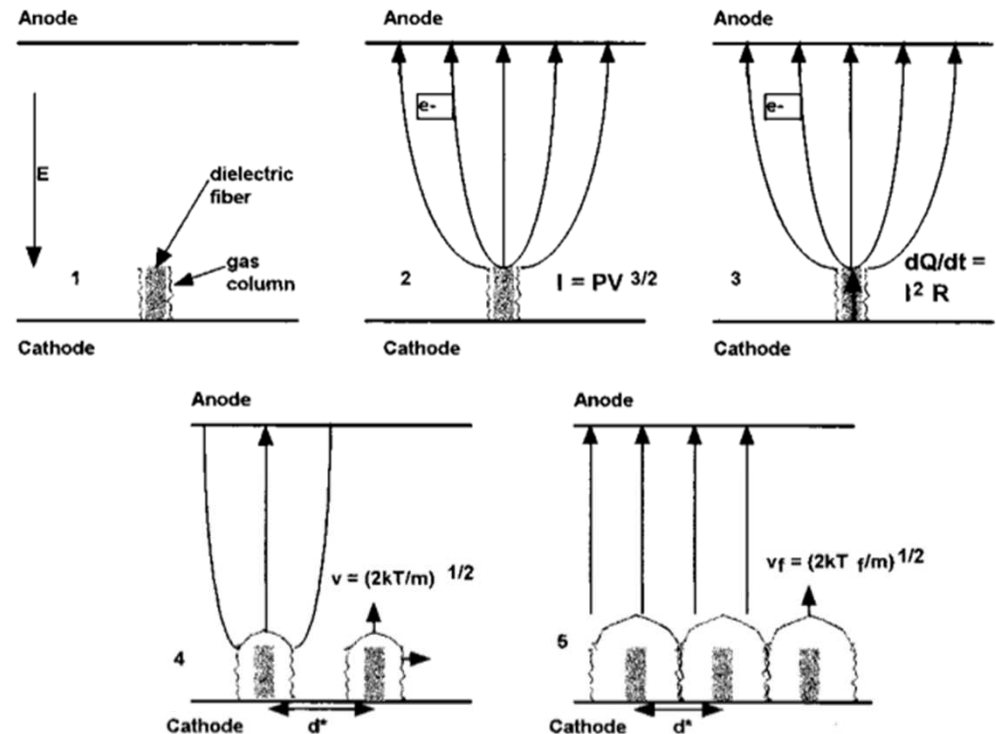


FIG. 10. Proposed model of velvet behavior: (1) Surface flashover generates a cold, dense plasma/gas column. (2) The electric field extracts a space-charge-limited current. (3) The current resistively heats the gas. (4) The gas columns expand at a rate determined by the gas temperature. (5) The gas continues to expand into the anode-cathode gap.

R. B. Miller, J. Appl Phys. **84**, 3880 (1998).

# Explosive Field-Emitter Cathodes

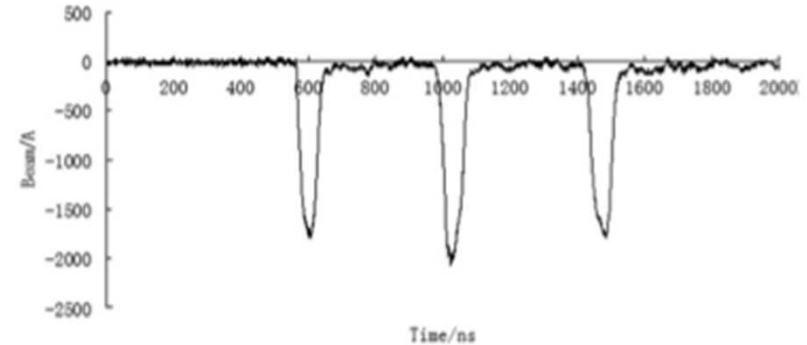
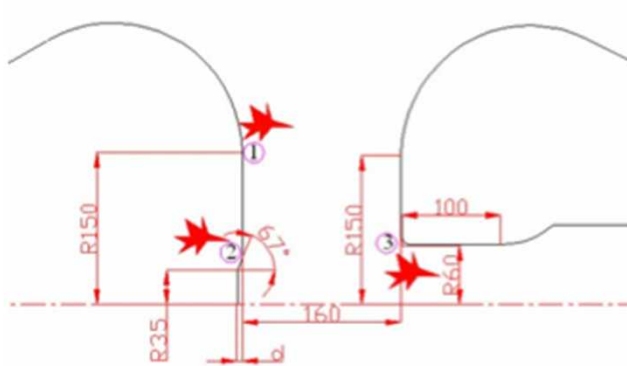


FIG. 3. Pulsed beams collected by the Faraday cup located in the anode hole. According to Figs. 2 and 3, the diode's perveances of the three pulses are not same.

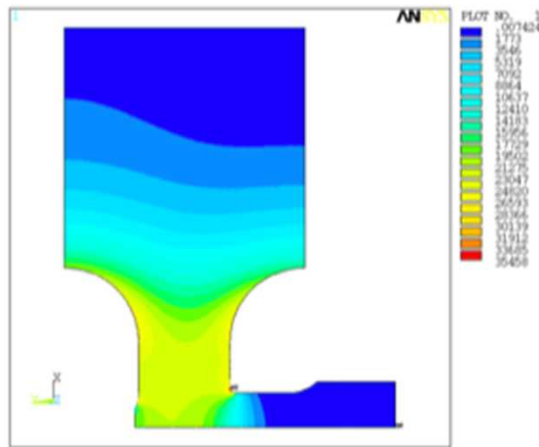


FIG. 5. (Color) Drawing of the configuration (top) and electric field map (bottom) of the diode.

**DRAGON injector with 160 mm gap spacing sees multi-pulse (400ns pulse gap) current variation probably due to plasma formation**

Z. Kaizhi et al, PR-STAB **9**, 080401 (2006).

$$t_f = d/v_f = 0.16 - 1.6 \mu s$$

# Thermionic Cathodes

- Thermionic cathodes use heated metals to release a high current density. The emitted electrons are part part of the high temperature tail which can overcome the metals work function.
- The emitted current density is well described by the Richardson-Dushman equation:

$$J_{RD} = \left(1.2 \times 10^6 \text{ A/m}^2 \text{ K}^2\right) T^2 e^{-\phi/kT}$$

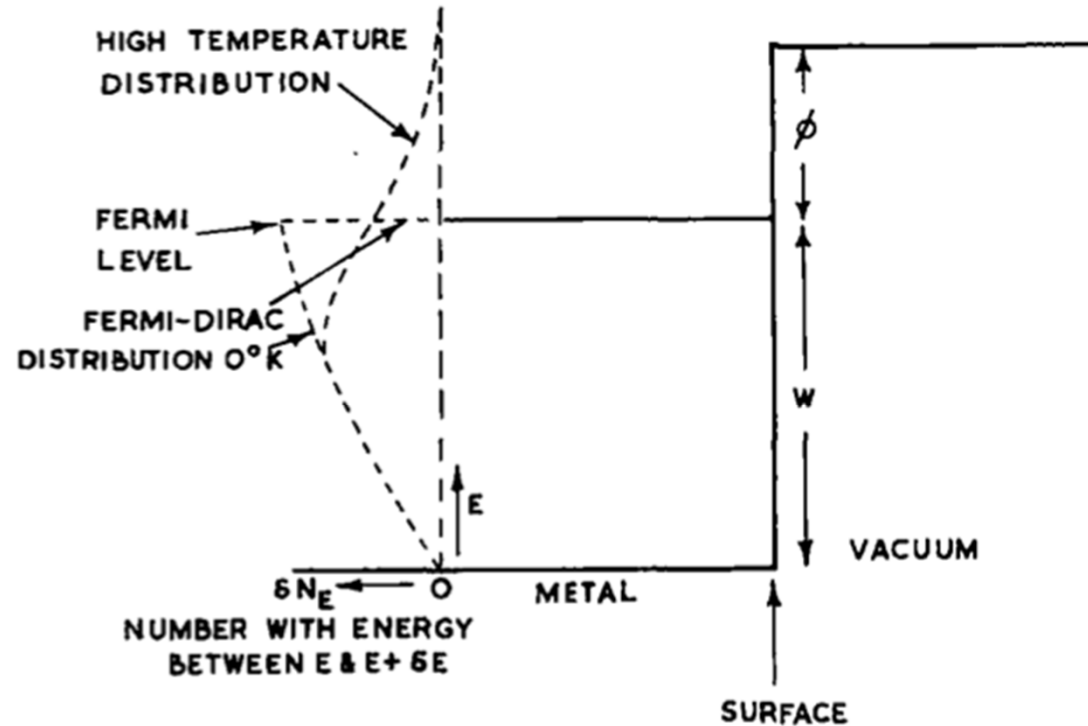


Figure 1. Potential diagram of clean metal.

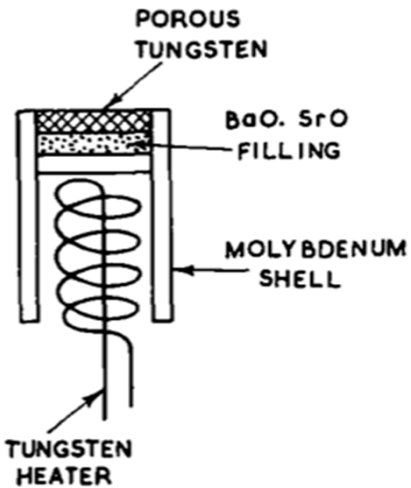
# Thermionic Cathodes

## Clean metal surface characteristics

| Metal | Melting point °K | Temperature · K for $10^{-7}$ torr vapour pressure | Richardson constants |             | Usable emission $A/cm^2$ |
|-------|------------------|--|----------------------|-------------|--------------------------|
|       |                  |  | A $Acm^{-2}T^{-2}$   | $\phi_0$ eV |                          |
| W     | 3640             | 2520   | 80                   | 4.54        | $4 \times 10^{-1}$       |
| Ta    | 3270             | 2370   | 60                   | 4.10        | $6 \times 10^{-1}$       |
| Re    | 3440             | 2330   | 700                  | 4.7         | $2.6 \times 10^{-2}$     |
| Mo    | 2890             | 1970   | 55                   | 4.15        | $5 \times 10^{-3}$       |
| C     | 4400             | 2030   | 48                   | 4.35        | $2 \times 10^{-3}$       |
| Pt    | 2050             | 1650   | 170                  | 5.40        | $2 \times 10^{-8}$       |
| Ni    | 1730             | 1270   | 60                   | 4.1         | $5 \times 10^{-9}$       |
| Ba    | 1120             | 580  | 60                   | 2.11        | $1 \times 10^{-11}$      |

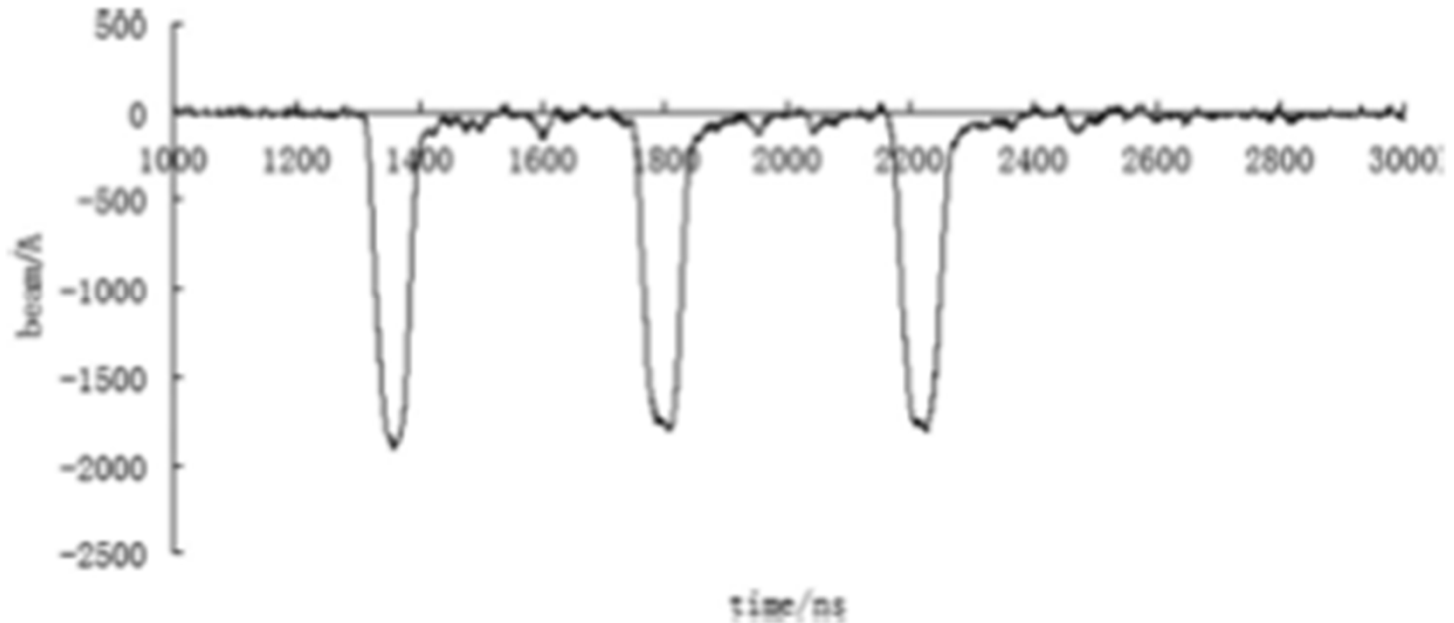
## Contaminated Tungsten

| Surface Monolayer | Work Function eV |
|-------------------|------------------|
| Clean             | 4.54             |
| Ce                | 2.7              |
| Th                | 2.7              |
| Ba                | 1.6              |
| Cs                | 1.5              |



**Barium dispenser cathode: Heated barium diffuses through porous tungsten to form a monolayer with low work function. These are commonly found in high-power microwave tubes.**

# Thermionic Cathodes



**DRAGON injector sees a small current variation in multi-pulse dispenser cathode (400ns pulse gap) operation. But is their variation small enough?**

# Photocathode Sources

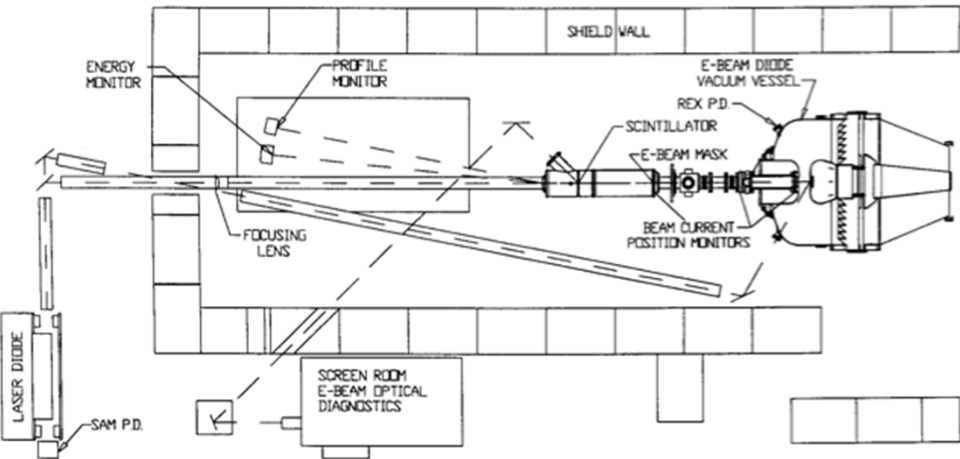


Figure 2. Layout of REX Electron-Beam Facility with Excimer Laser Diode.

- Photocathode sources use a laser to photoemit electrons from a metal or semiconductor surface.
- They are traditionally used when low current, excellent beam quality is needed, e.g. FELs, linear colliders, but can be configured to produce multi-kA beams.
- ArF laser on Al-6061 photocathode produced a quantum efficiency (# of e-emitted per incident photon) of  $10^{-3}$  at DARHT

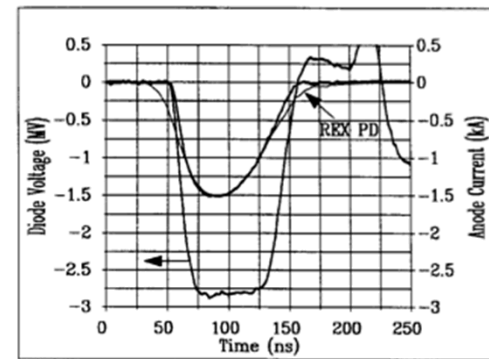


Figure 5. VI of Photo-Cathode at 8.3 MW.

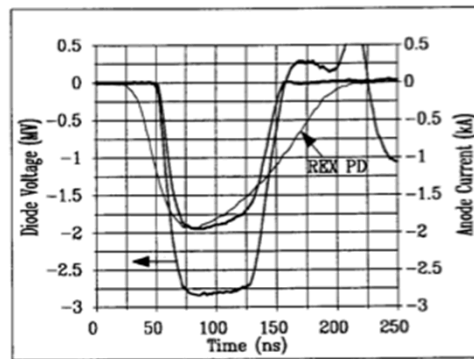


Figure 6. VI of Photo-Cathode at 11.6 MW.

R.L. Carlson, et al., DARHT  
Technical Notes No. 53, 1996.

# Comparative Performance of Cathodes

|                         | Peak Current  | Beam Emittance   | Current Control Limits  |
|-------------------------|---|--|---|
| Explosive Field-Emitter | Multi-kA  | 8000 $\pi$ mm-mrad <sup>1</sup><br>(Velvet)<br>3000 $\pi$ mm-mrad <sup>1</sup><br>(Carbon Fiber) | gas column expansion/plasma formation effect<br>effects additional pulses |
| Thermionic              | Multi-kA  | $\sim$ 2000 $\pi$ mm-mrad <sup>2</sup>   | ?   |
| Photocathode            | Typically 10's-100's A, but multi-kA has been demonstrated at DARHT | 5.6 $\pi$ mm-mrad <sup>3</sup> at $\sim$ 100 A peak current                                      | Sub-ps current control demonstrated in rf photocathodes                   |

**Q: Why is emittance important?**

**A: The minimum beam spot size is proportional to  $\epsilon^{1/2}$  from beam transport theory.**

<sup>1</sup>D. A. Shiffler et al, IEEE Trans. Plasma Sci. **30**, (2002).

<sup>2</sup>M. Reiser, Theory and Design of Charged Particle Beams (1994).

<sup>3</sup>J. F. Schmerge et al, SLAC-PUB-8065, (2002).

# Conclusions

- Explosive field-emitter and thermionic dispenser cathodes have been thoroughly tested in the high peak current regime ( $\sim 2\text{kA}$ ), and are options for a multi-pulse injector. Both cathodes produce higher emittance beams, and in addition, the explosive field-emitters may have difficulty with multi-pulse due to gas column expansion.
- Photocathodes potentially offer the overall best beam quality and current control. They are primarily used for lower peak current applications, but have been demonstrated in the multi-kA regime in early DARHT work. This technology is not “off-the-shelf”, and probably requires further R&D into the best laser system/photocathode material for optimizing quantum efficiency.
- My recommendation for a future radiography machine is to start with a well-established technology, either explosive field emitter or a thermionic cathode. However, we should allow flexibility in the design to incorporate a photocathode at a later time for better beam quality.