Cornell University
Laboratory for Elementary-Particle Physics

USPAS course on
Recirculated and Energy Recovered Linacs

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Electron Sources: Introduction, Parameters, Physics of Electron Emission

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  - light source
  - nuclear physics
  - ion cooling
  - electron-ion collider
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Introduction

With a short-lived (≤ μs) electron life-cycle in R&ERLs, the emphasis for delivering the beam of appropriate quality for a given application shifts almost entirely on the injector.

One way to define an injector: a part of the R&ERL up to (and including) the merge with the returning high-energy beam.

The injector determines many of the key properties of the beam (can be degraded downstream, but never improved!)

- beam current & timing structure
- horizontal & longitudinal emittances
- polarized & magnetized beam

Interface of different disciplines

Since R&ERLs can be applied to a host of different applications, each with its own parameter set from the injector, no single injector design or approach can be adequate.

Thermal Emission Photoemission Field Emission

Injectors are found at the interface of various disciplines & techniques:

- solid state & material science (cathode physics)
- lasers (photoemission)
- complex beam dynamics: space charge, single species plasma, governed by its Debye length and plasma frequency
- high field guns (part of the injector where beam is born), surfaces at ultrahigh gradients
- plus the 'usual' accelerator physics

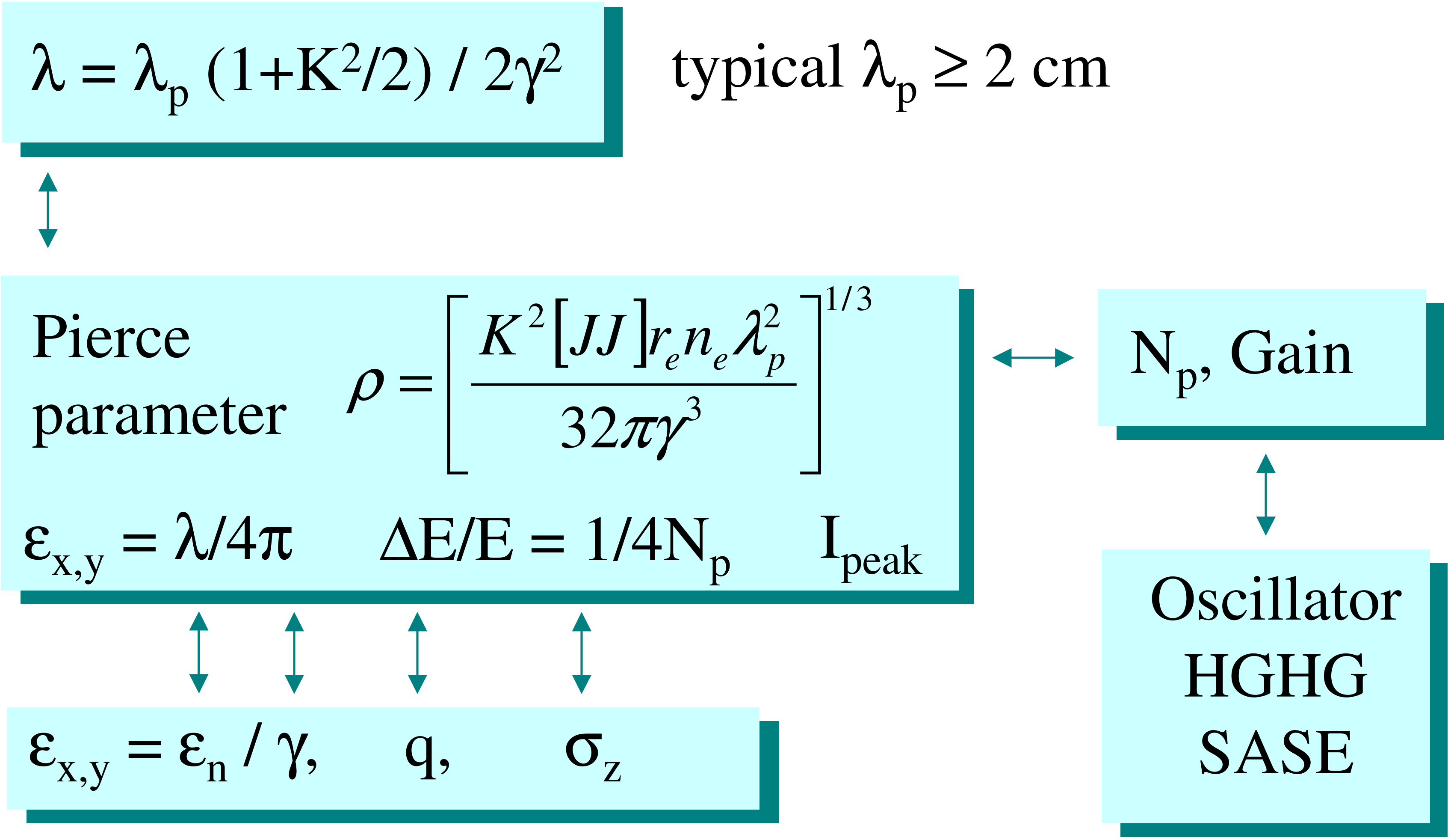
Applications

R&ERL applications

- Light sources
  - Spontaneous
  - Free electron lasers
- Nuclear physics (CEBAF)
- Electron cooling of ions
- Electron-ion collider

Beam parameters vary from sub-pC to several nC charge / bunch, less than mA to Ampere average current, may have ‘special’ requirements: polarization and magnetized beam

FELs



$\lambda = \lambda_p \, (1+K^2/2) \, / \, 2\gamma^2$

typical $\lambda_p \geq 2$ cm

Pierce parameter $\rho = \left[\dfrac{K^2 [JJ] r_e n_e \lambda_p^2}{32 \pi \gamma^3} \right]^{1/3}$

$\varepsilon_{x,y} = \lambda/4\pi$ $\Delta E/E = 1/4N_p$ I_{peak}

$\varepsilon_{x,y} = \varepsilon_n / \gamma$, q, σ_z

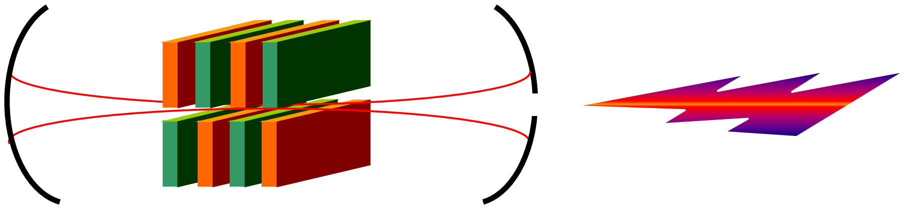
N_p, Gain

Oscillator
HGHG
SASE

FELs (contd.)

$\varepsilon_{x,y} = \lambda/4\pi$ $\Delta E/E = 1/4N_p$ I_{peak}

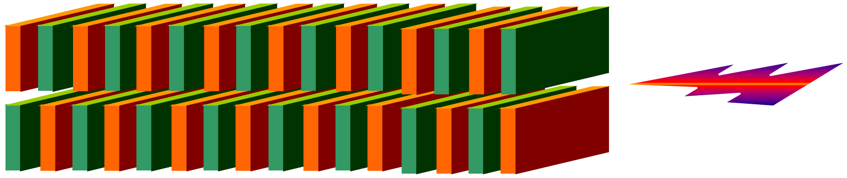
Low Gain



Longer wavelength → high reflectivity mirrors → oscillator configuration → short undulator

$\varepsilon_n \sim 10\ \mu\text{m},\ E \leq 100\ \text{MeV}$
$q \sim 0.1\ \text{nC}$ for $\lambda \sim 1\mu\text{m}$

High Gain



Shorter wavelength (XUV and down) → high gain → long undulator → more stringent specs

$\varepsilon_n \sim 1\ \mu\text{m},\ E > \text{GeV}$
$q \sim 1\ \text{nC}$ for $\lambda \sim 10\ \text{nm}$

For high power FELs $I \sim 0.1\text{-}1\ \text{A}$

Hard X-ray ERL light sources

3rd GLS storage rings, workhorse of X-ray science, are spontaneous emission sources (photons produced = $N_e \times$ single electron radiation). Various figures of merit can be used to characterize the source, e.g.

Flux [ph/s/0.1%bw] $\propto I$

Brightness [ph/s/0.1%/mm^2/mr^2] $\propto I/(\varepsilon_x \oplus \lambda/4\pi)(\varepsilon_y \oplus \lambda/4\pi)$

Improving flux beyond what is possible with a storage ring is unlikely, but brilliance can be improved (presently best values 10^{20}–10^{21} ph/s/0.1%/mm^2/mr^2).

$\varepsilon_n \sim 0.6\ \mu\text{m}$, $q \sim 0.08$ nC, $I \sim 100$ mA, $E \sim 5$ GeV
for brilliance of $\sim 10^{22}$ ph/s/0.1%/mm^2/mr^2

Nuclear physics

Electrons are a probe.

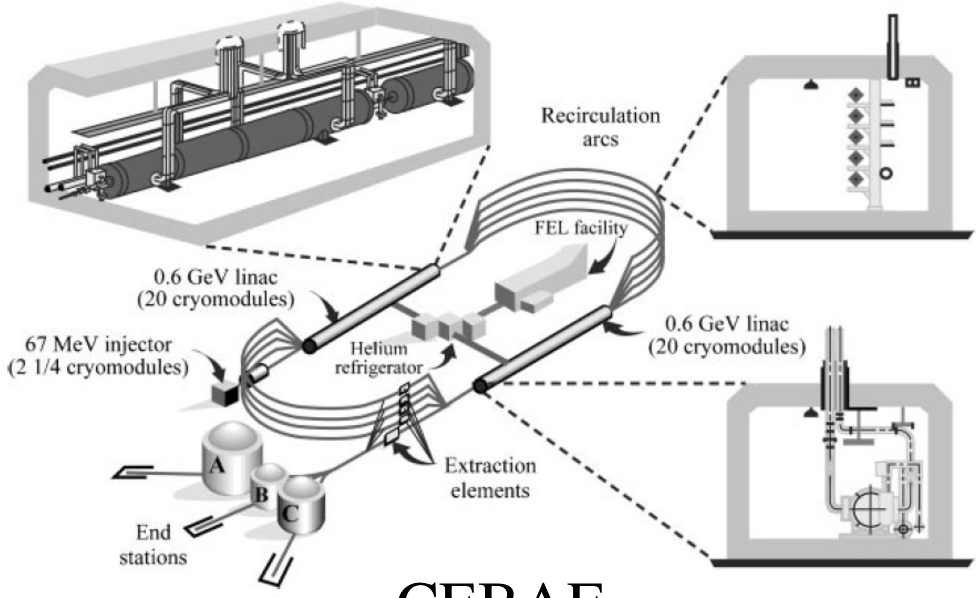
E = 6 GeV

I = 200 µA

$q < 0.3$ pC

$\Delta E/E = 2.5 \times 10^{-5}$

Polarization > 75 %



CEBAF

Polarization is given by $$\frac{I(\uparrow)-I(\downarrow)}{I(\uparrow)+I(\downarrow)}$$

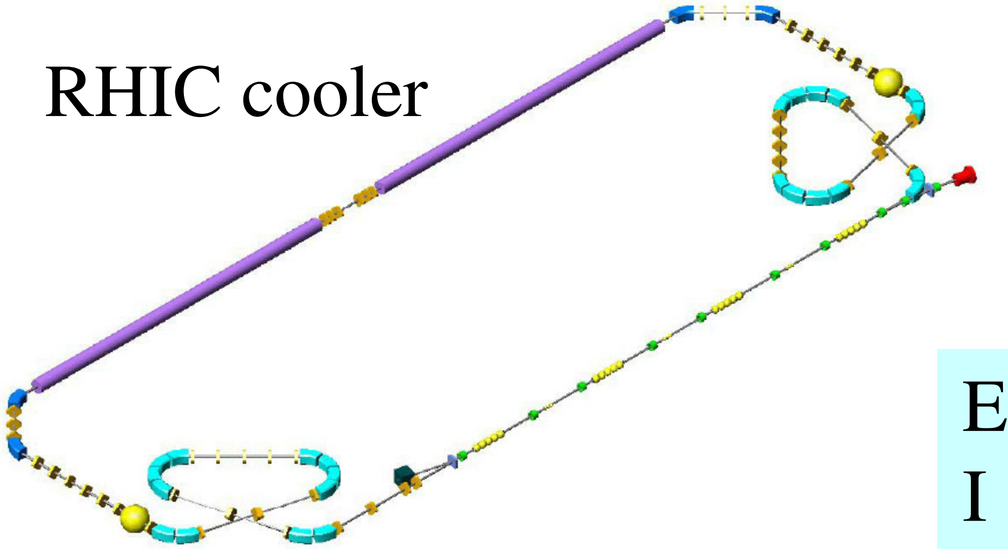
where I(↑) is the number of electrons with spin ‘up’ and I(↓) is the number of electrons with spin ‘down’ along a given axis.

Electron cooling of ions

- There is no radiative cooling in ion storage rings due to their large mass. One way to reduce ions phase space volume is to co-propagate ions with a bunch of cold electrons (same $\beta = v/c$). In the rest frame, the picture resembles two-species plasma with different temperatures $T_{ion} > T_{electron}$ (interaction will heat up electrons and cool down ions).
- High density of electrons is required for tolerable cooling rates.
- Interaction takes place in a long focusing solenoid. To avoid enlarged 2D emittance a so-called 'magnetized' beam is needed from the source. We will discuss magnetized beam and Busch's theorem later in this lecture.

Electron cooling of ions (BNL)

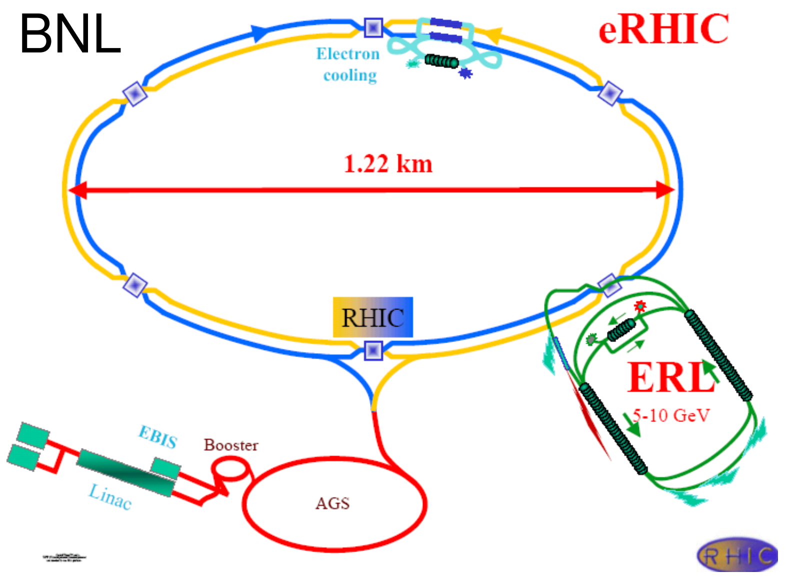
RHIC cooler

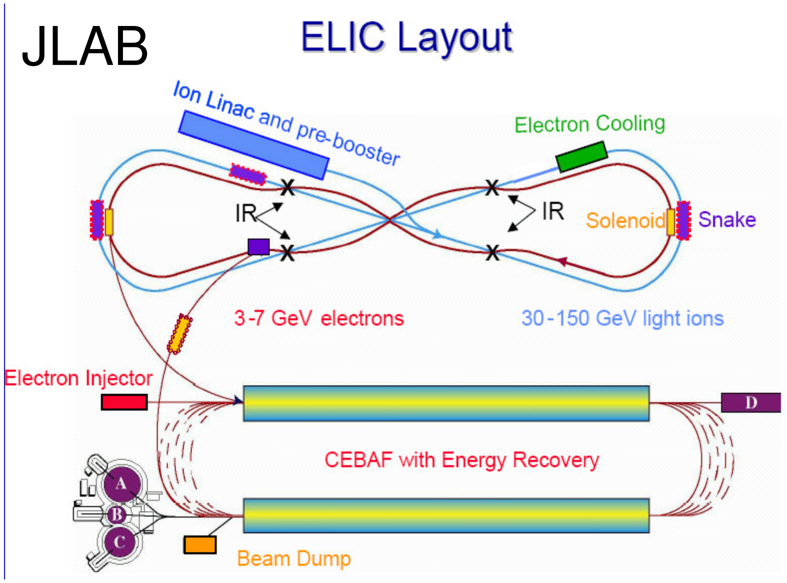


one parameter set

E = 55 MeV
I = 200 mA
q = 20 nC
$\Delta E/E = 3 \times 10^{-4}$
magnetized beam

Electron-Ion collider





$E = 2\text{-}10$ GeV $I \sim 100$s mA $\varepsilon_n \sim 10$s mm-mrad

polarized electrons from the gun

Injector needs: bird's eye view

- The underlying feature of present and future R&ERLs is CW operation → high rep. rate, high current
- FELs: need a beam close to the diffraction limit → emittance; need high peak current to lase (kA) → charge per bunch, longitudinal emittance for low final/injection energy ratio
- ERL spontaneous LS: beam brightness is paramount → $I/\varepsilon_x\varepsilon_y$; medium to low charge per bunch preferred
- Electron cooling: high bunch charge (many nC) and current (0.1-1 Ampere); magnetized beam
- Electron-ion collider: polarized source with high average current

Injector needs (contd)

- It is literally impossible to cover all the areas circumscribed by injectors needed by various R&ERL in the framework of this course
- We'll concentrate on unique challenges of ERL sources, which mainly demand
  - High average current
  - Simultaneously with ultra-low emittance
- The choice of electron emission process is a key to subsequent electron source design
- But first let's discuss very briefly the state-of-the-art

State-of-the-art: BOEING gun

Photocathode Performance:

Photosensitive Material: K_2CsSb Multialkali
Quantum Efficiency: 5% to 12%
Peak Current: 45 to 132 amperes
Cathode Lifetime: 1 to 10 hours
Angle of Incidence: near normal incidence

Gun Parameters:

Cathode Gradient: 26 MV/meter
Cavity Type: Water-cooled copper
Number of cells: 4
RF Frequency: 433 $x10^6$ Hertz
Final Energy: 5 MeV(4-cells)
RF Power: 600 $x10^3$ Watts
Duty Factor: 25%, 30 Hertz and 8.3 ms

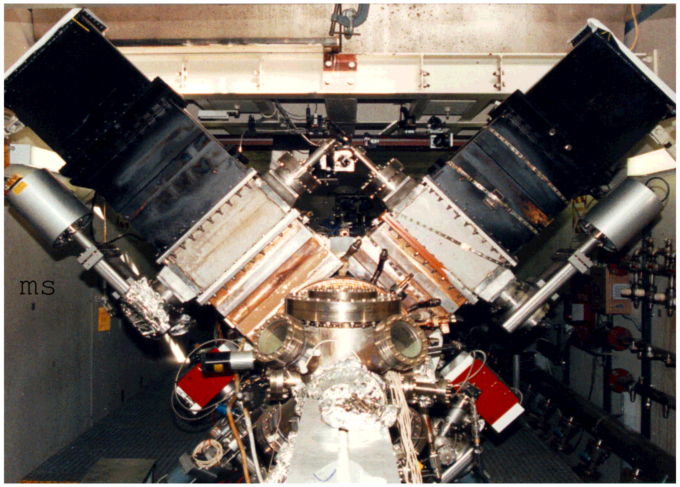
Laser Parameters:

Micropulse Length: 53 ps, FWHM
Micropulse Frequency: 27 $x10^6$ Hertz
Macropulse Length: 10 ms
Macropulse frequency: 30 Hertz
Wavelength: 527 nm
Cathode Spot Size: 3-5 mm FWHM
Temporal and Transverse Distribution: gaussian, gaussian
Micropulse Energy: 0.47 microjoule
Energy Stability: 1% to 5%
Pulse-to-pulse separation: 37 ns
Micropulse Frequency: 27 $x10^6$ Hertz

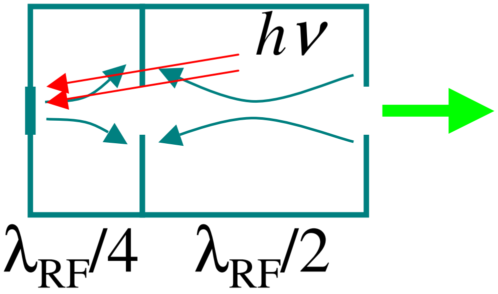
Gun Performance:

Emittance (microns, RMS): 5 to 10 for 1 to 7 nCoulomb
Charge: 1 to 7 nCoulomb
Energy: 5 MeV
Energy Spread: 100 to 150 keV

433 MHz RF Gun



32 mA avg. current

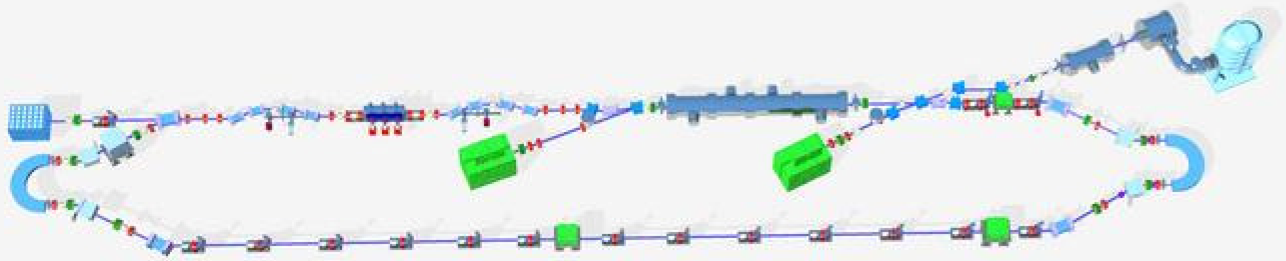


State-of-the-art: JLAB FEL inj.

500 kV (350) DC gun

- Cs:GaAs photocatode
- max current 9.1 mA, routine 5 mA
- best simulated emittance 5 µm, measured ×2 larger at 60 pC
- work on 100 mA gun underway to drive high power IR FEL

9.1 mA avg. current

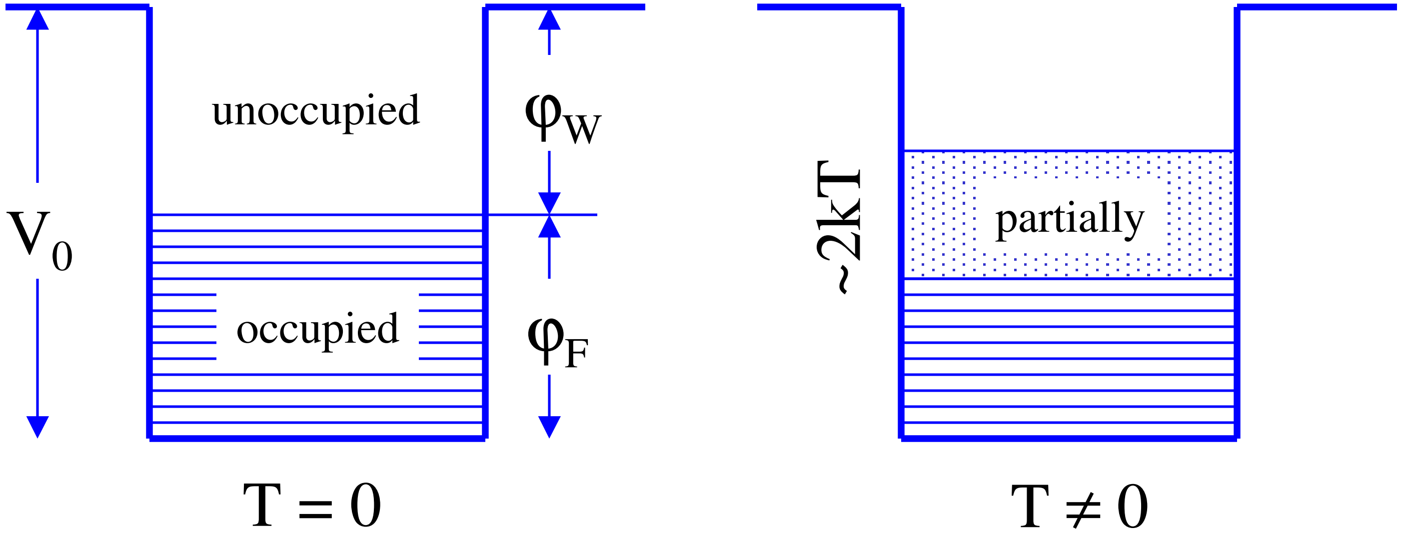


10 kW IR FEL

Cathode figures of merit

- available current density
- energy and momentum distribution of emitted electrons
  - transverse temperature $\varepsilon_{n,th} = \sigma_{\perp}\sqrt{\frac{E_{th}}{mc^2}}$
  - response time
- lifetime (resistance to contamination)

Emission: thermal in metals



Richardson-Dushman equation (1923)

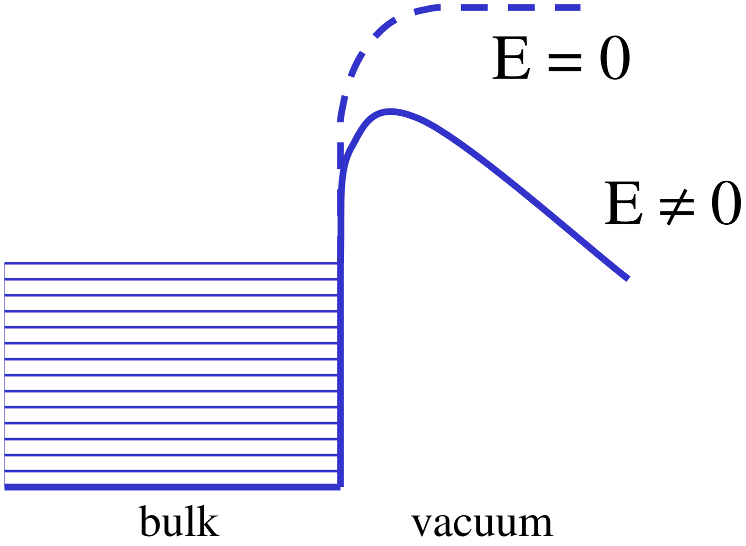
current density $$J = AT^2 \exp\left[-\frac{e\varphi_W}{kT}\right]$$

$A = 120$ A/(cm^{2}K^2)

$\varphi_W = 4.5$ V (tungsten)

$\varphi_W = 2.0$ V (dispenser)

Emission: Schottky correction



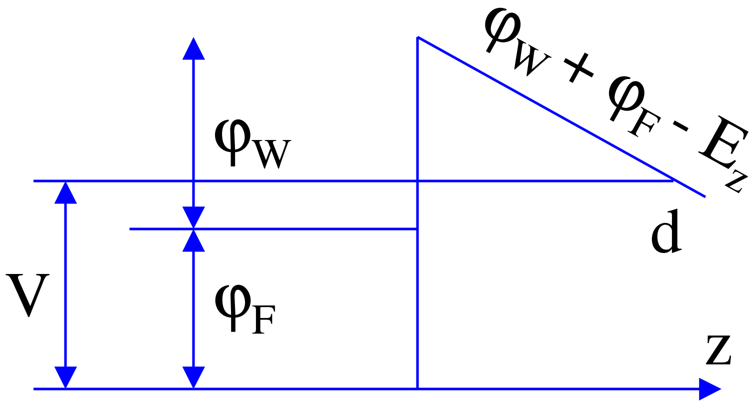
$$J = AT^2 \exp\left[-\frac{e\varphi_W^*}{kT}\right]$$

External field lowers work function $\varphi_W^* \to \varphi_W - \Delta\varphi$

Schottky correction $\Delta\varphi = \sqrt{\dfrac{eE}{4\pi\varepsilon_0}}$ $\Delta\varphi[\mathrm{V}] = 0.038\sqrt{E[\mathrm{MV/m}]}$

Emission: Fowler-Nordheim tunneling

Schottky correction does not include probability of escaping from a finite width potential barrier that follows from quantum mechanics. In 1928 Fowler and Nordheim have published a paper where they derived current density from this effect.



$$J_z = \int_0^\infty e P v_z n(v) dv$$

$$P \propto \exp\left[-\frac{4}{3}\sqrt{\frac{2m}{\hbar^2}}\frac{(e\varphi_W + e\varphi_F - W_z)^{3/2}}{eE}\right]$$

(A/cm²)

$$J_z = 6.2\times10^{-6}\frac{\sqrt{\varphi_F/\varphi_W}}{\varphi_F+\varphi_W}E^2\exp\left[-6.8\times10^7\frac{\varphi_W^{3/2}}{E}\right]$$

(V)

(V/cm)

Emission: field enhancement

Interestingly, F-N dependence of field emission with E is the same as the functional R-D dependence of thermal emission with T.

In reality, field emission fits F-N dependence if E → Eβ. β is known as an enhancement factor that translates macroscopic field E to a local value (local geometry dependant).

In summary,

$$J_{thermal} = AT^2 \exp\left[-\frac{e\varphi_W}{kT}\right]$$

$$J_{Schottky} = AT^2 \exp\left[-\frac{e(\varphi_W - B\sqrt{\beta E})}{kT}\right]$$

$$J_{field} = C\beta^2 E^2 \exp\left[-\frac{D}{\beta E}\right]$$

Emission: photoeffect

Photoemission offers several advantages over thermal/field emission:

- Higher current density
- Bunched beam is generated through a laser with appropriate time structure. No need for chopping / extensive bunching as in the case of thermal emission (shortest pulse available through a grid pulser is ~ ns, while L-band RF needs bunches ~10 ps long – readily available from photocathodes).
- Colder beam (lower thermal emittance) is possible
- Polarized electrons from special photocathodes

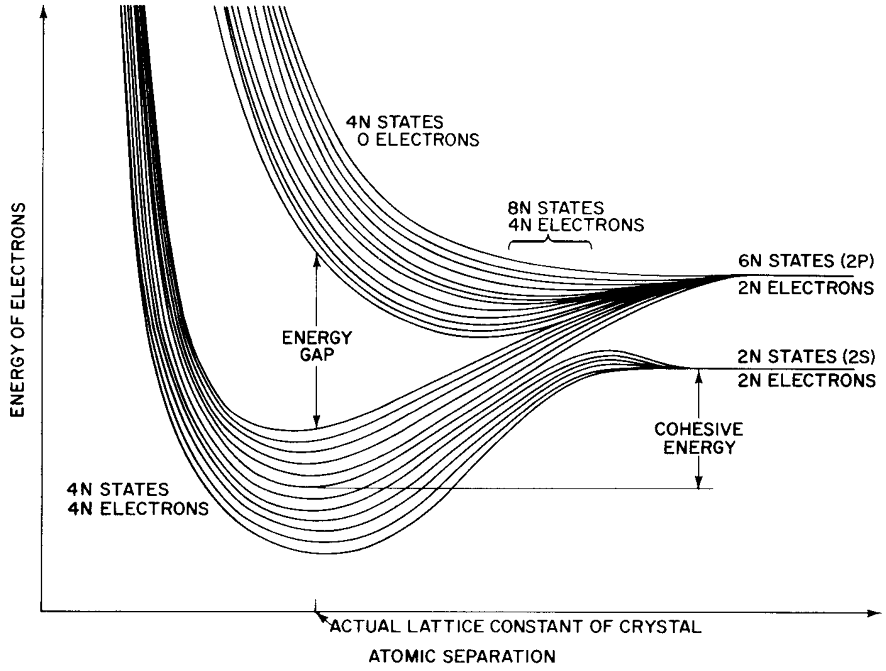
Interesting historical overview of photocathode development
Alfred H. Sommer, Brief history of photoemissive materials, SPIE Proc 2022 (1993) pp. 2-17

Photocurrent

$$I[\text{mA}] = \frac{\lambda[\text{nm}]}{124} \times P_{laser}[\text{W}] \times \eta[\%] \longleftarrow \frac{N_e}{N_{ph}}$$

- For *metals* such as copper work function is 4.5 eV → UV light is required (frequency multiplication in nonlinear medium crystals)
- Furthermore, η is low ($< 10^{-3}$) due to electron-electron scattering in conduction band (1/2 energy lost per collision on average)
- Metals have very fast response time (fs)
- Thermal emittance numbers vary, values quoted for thermal energy $E_{th} = 0.2\text{–}0.7$ eV
- In short, metals (Cu, Mg, etc.) are suitable for pulsed applications, but is a poor choice for a high average current gun

Photoemission: semiconductors

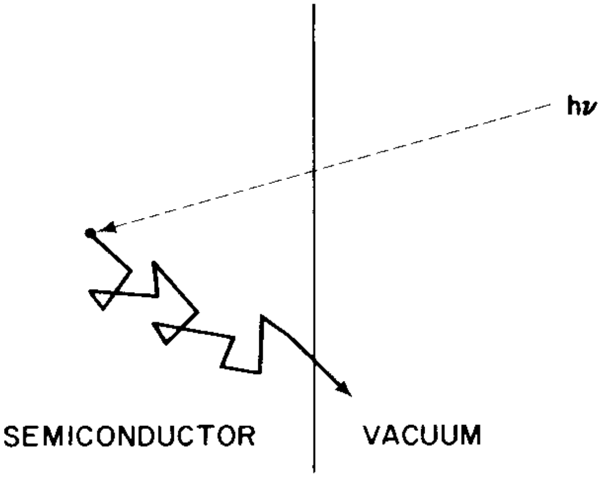


Energy banding of allowed levels in diamond as a function of spacing between atoms

Gap and availability of electrons in conduction band determines whether material is
Metal: ne ~ 10^{23} cm^{-3}
Semiconductor: gap < 3 eV; n_e (n_h) < 10^{20} cm–3
Insulator: gap > 3 eV; negligible n_e and n_h

Good quantum efficiency (10s %) available from semiconductor photocathodes (K_2CsSb, Cs_2Te, GaAs) & lower photon energy due to a smaller gap

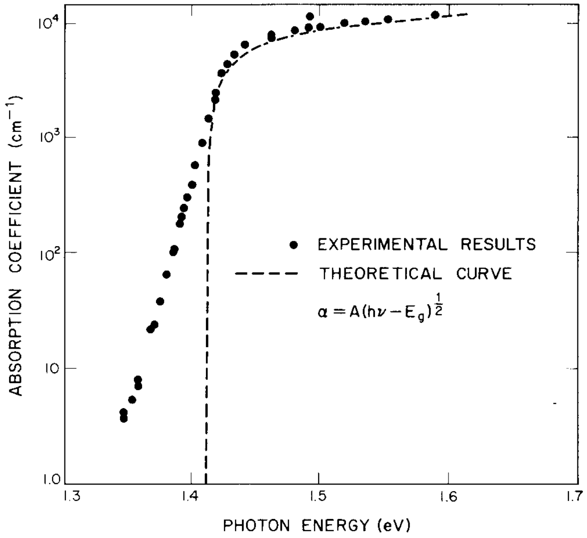
Spicer's three step model



(1) photon excites electron to a higher-energy state;

(2) electron-phonon scattering (~0.01–0.05 eV lost per collision);

(3) escape with kinetic energy in excess to E_{vac}

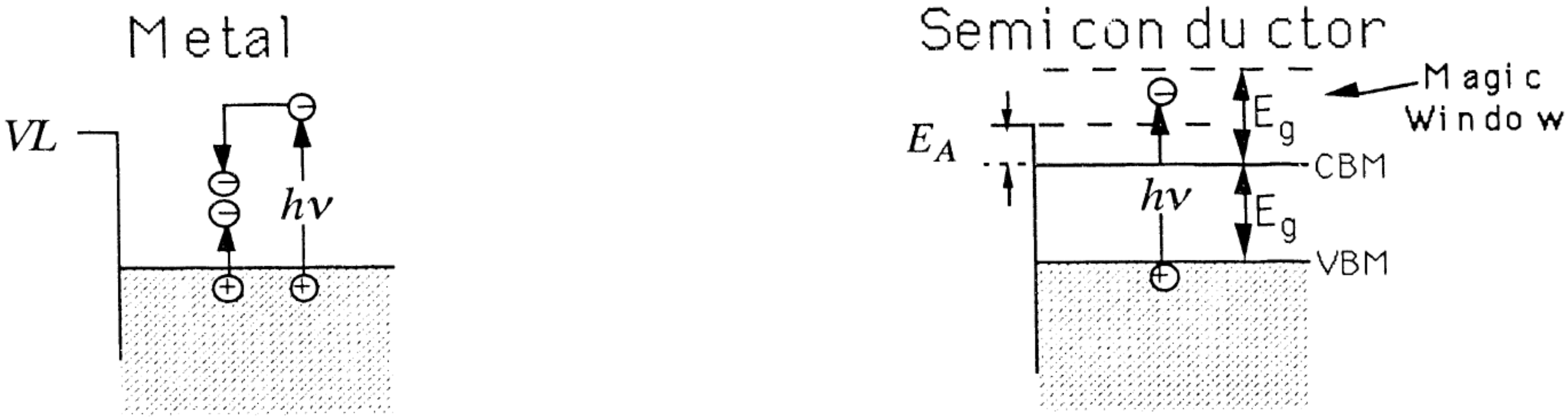


Absorption edge of GaAs at room temperature.

In GaAs the escape depth is sufficiently long so that photo-excited electrons are *thermalized* to the bottom of the conduction band before they escape.

Response time ~ (10^{-4} cm)/(10^{7} cm/s) = 10 ps (wavelength dependant)

Inelastic scattering mechanisms



(1) electron-electron scattering, lead to large energy loss per single collision (occurs in metals);

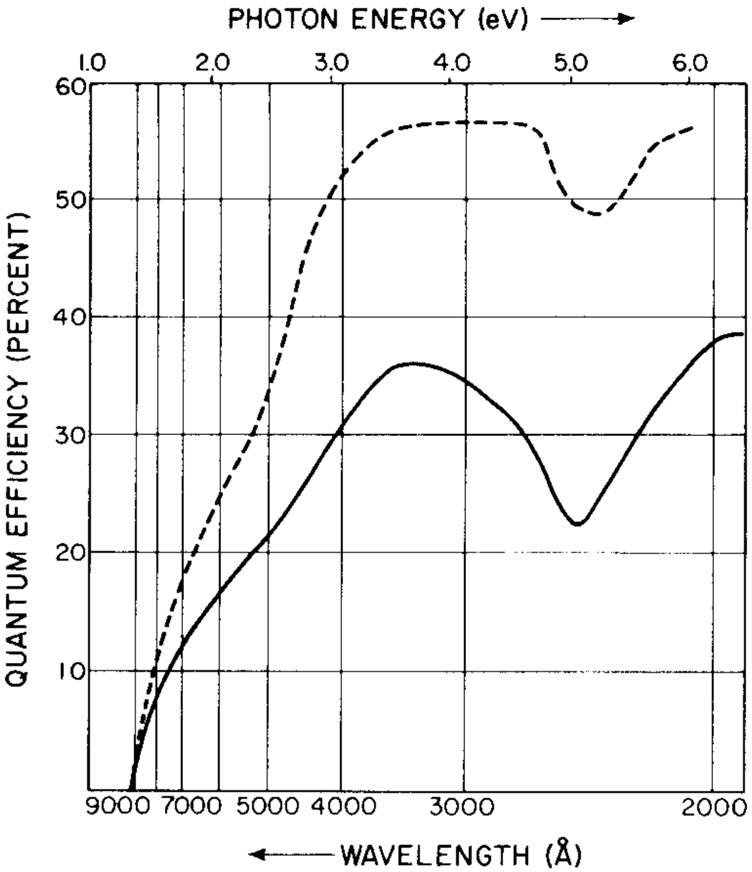
(2) electron-phonon scattering, takes multiple scattering events to deplete electron excessive energy;

(3) “magic window” – in semiconductors, if takes an excess kinetic energy > E_{gap} for e^-/e^- scattering to occur, so electrons excited with $E_{vac} < KE < E_{VBM} + 2E_{gap}$ have good chances of escape

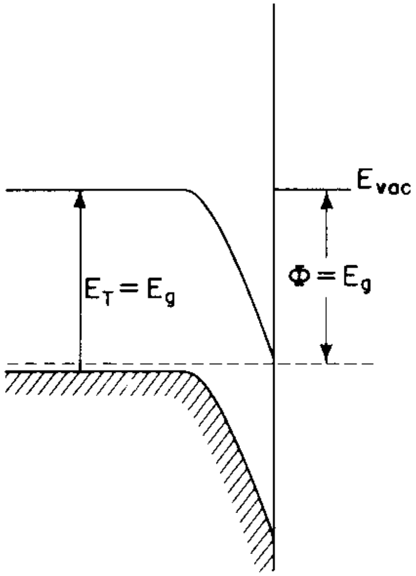
Negative electron affinity

Surface condition induces a space charge, which may bend the bands either up or down (bottom of conduction band in the bulk relative to E_{vac} is called electron affinity).

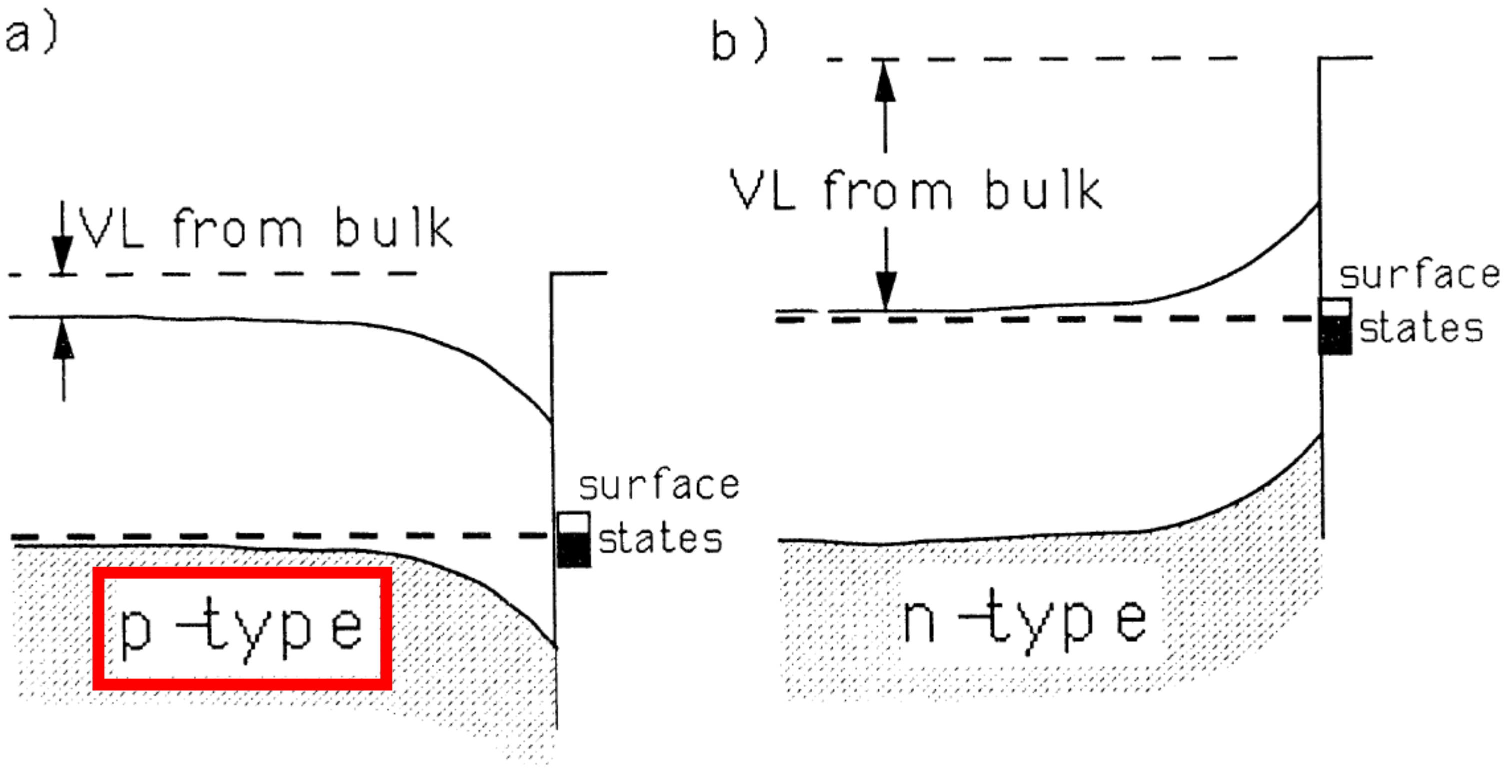
If thickness of a low φ_W material << mean free path → e^- can traverse the surface material without much loss → better quantum efficiency / reduced threshold



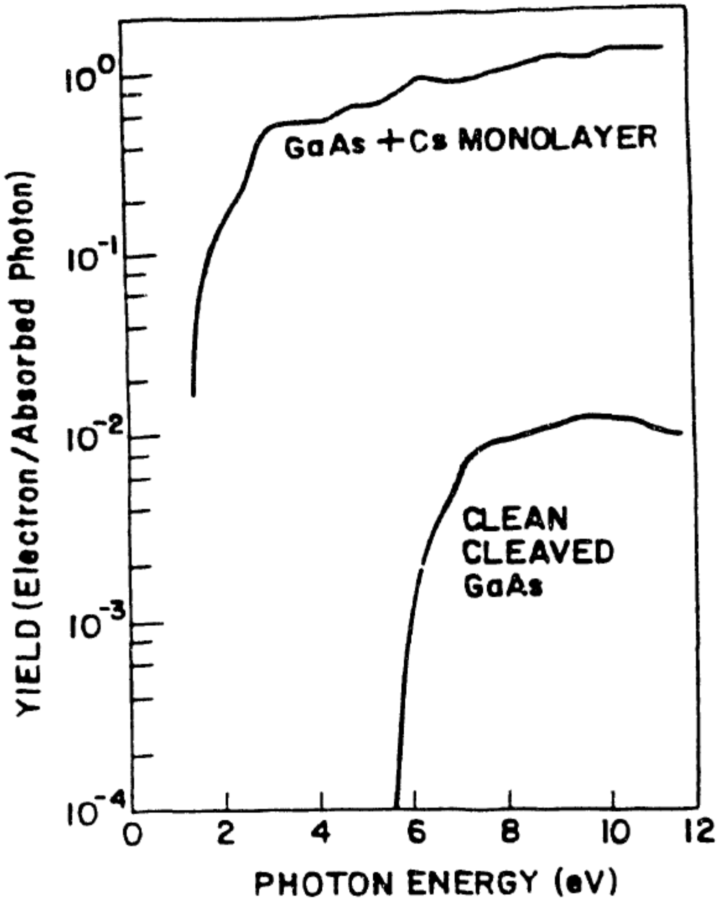
Cs:GaAs. Dashed line – Q.E. per absorbed photon



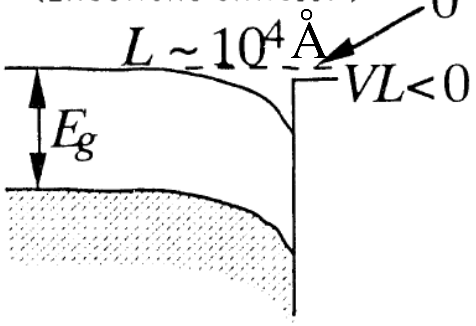
Bend-banding



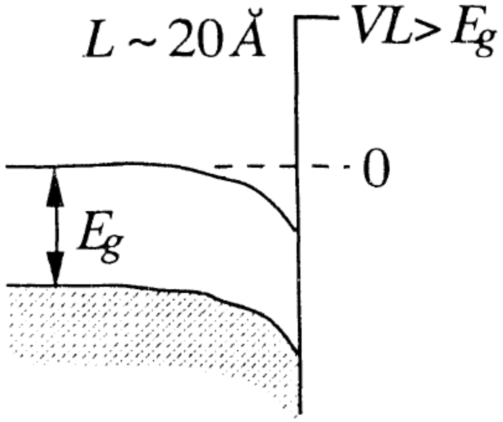
GaAs photocathode



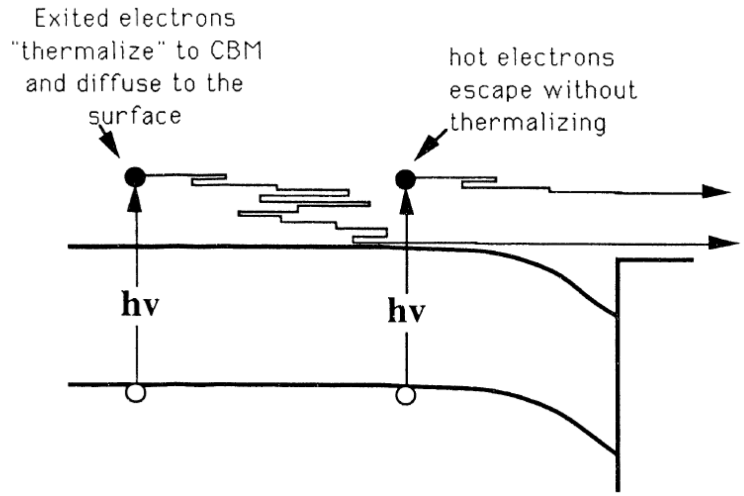
Large Magic Energy Window
(Excellent emitter)



Small or no
Magic Energy Window
(Very poor emitter)

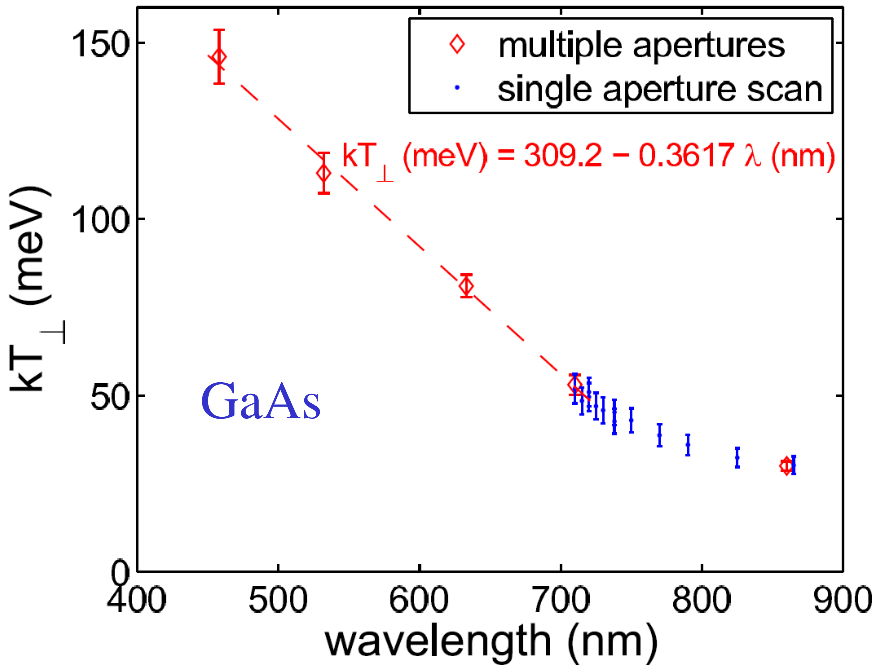


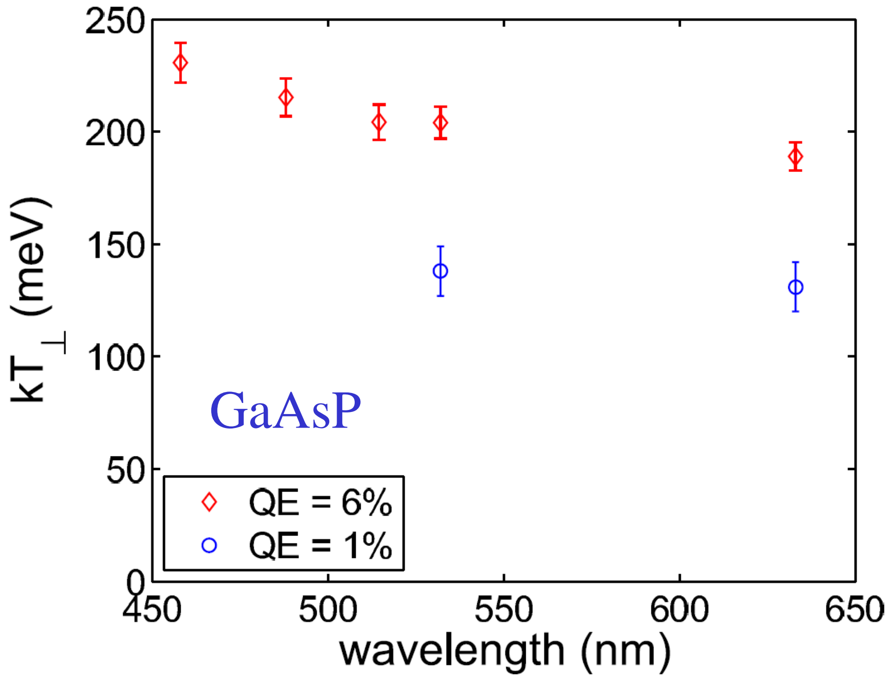
Thermal emittance



relates laser spot size to emittance

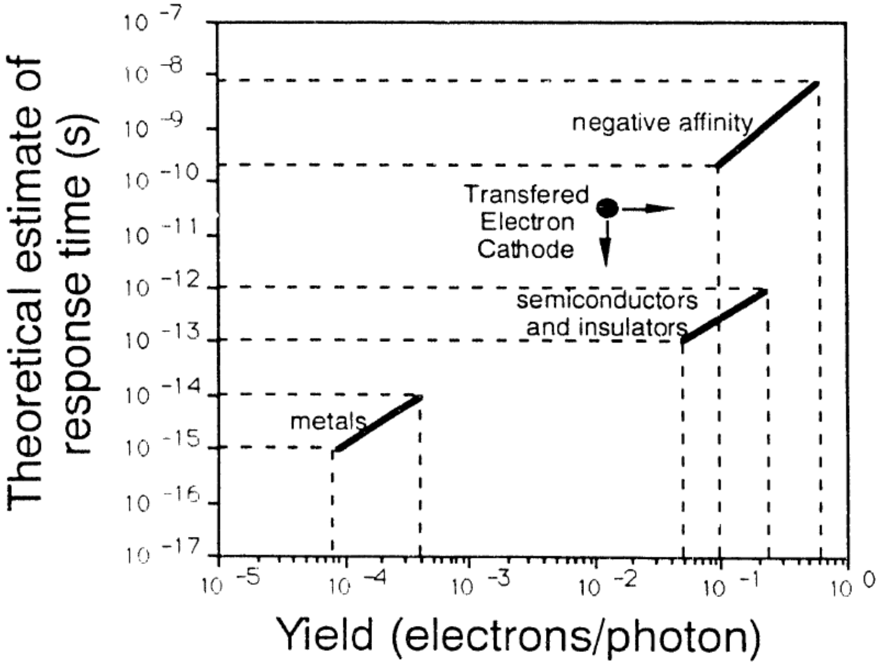
$$\varepsilon_{n,th} = \sigma_{\perp}\sqrt{\frac{E_{th}}{mc^2}}$$



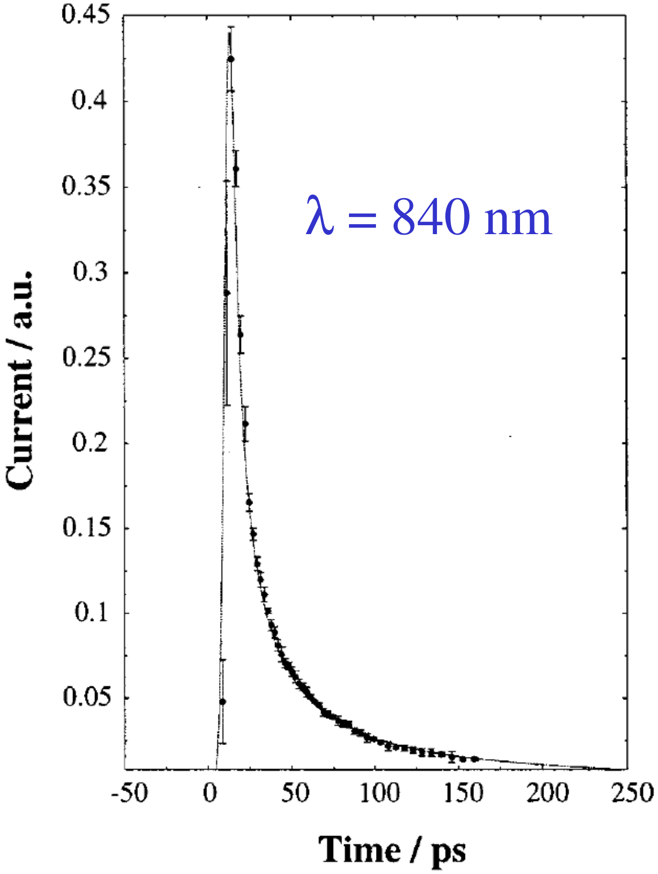


Temporal response

- Because the escape length from high QE cathodes is long, one may expect a long temporal tail
- Indeed, long emission tails have been measured for GaAs excited with near band gap energy photons



P. Hartmann et al., J. Appl. Phys. 86 (1999) 2245



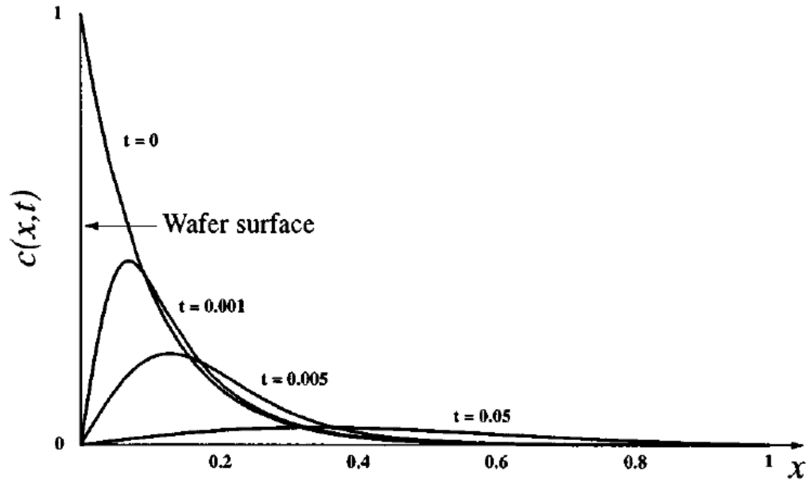
Diffusion model

$$\frac{\partial c(h,t)}{\partial t} = D\frac{\partial^2 c(h,t)}{\partial h^2}$$

subject to:

$$c(h,t=0) = c_0 e^{-\alpha h}$$

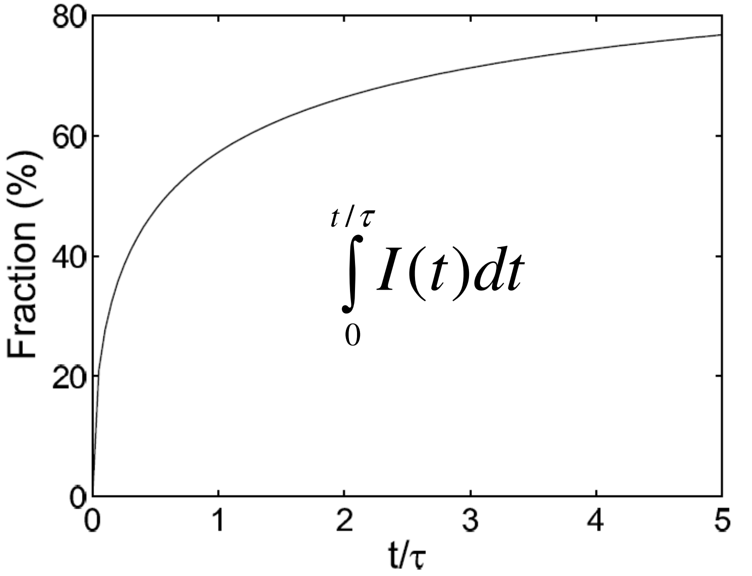
$$c(h=0,t) = 0$$



$$I(t) \propto \frac{\partial}{\partial t}\int_0^\infty c(h,t)dh.$$

$$I(\kappa) \propto \frac{1}{\sqrt{\pi\kappa}} - \exp(\kappa)\,\mathrm{erfc}(\sqrt{\kappa})$$

$$\kappa \equiv t/\tau, \text{ where } \tau \equiv \alpha^{-2}D^{-1}$$

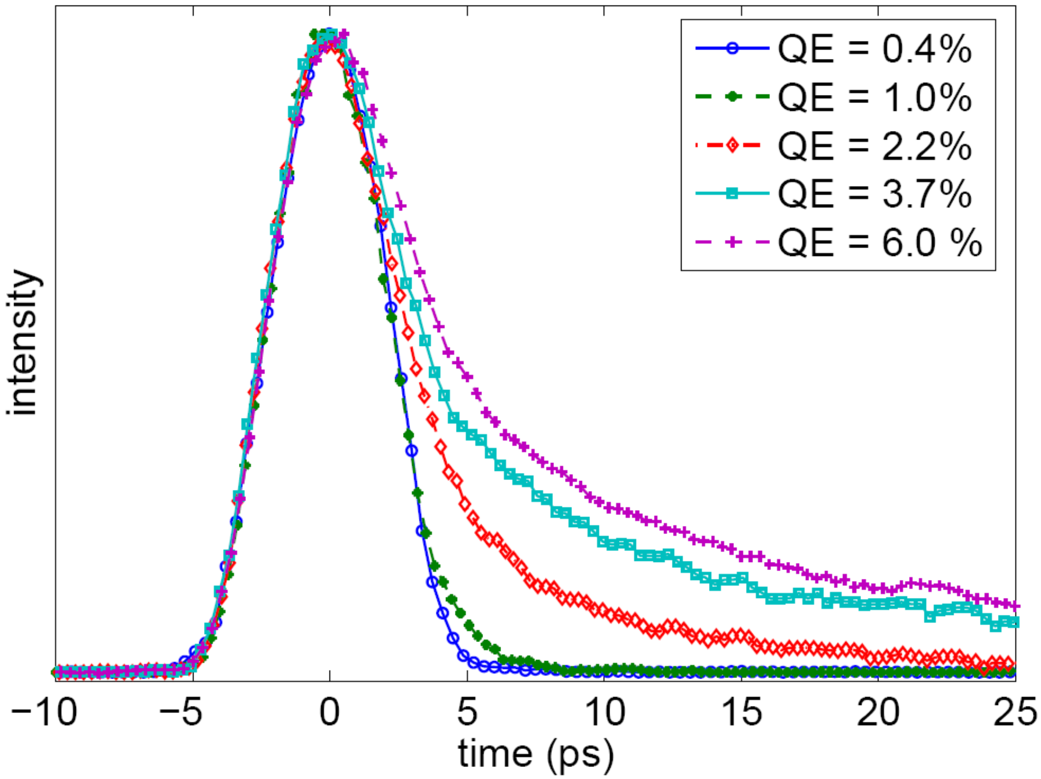


Wavelength dependence

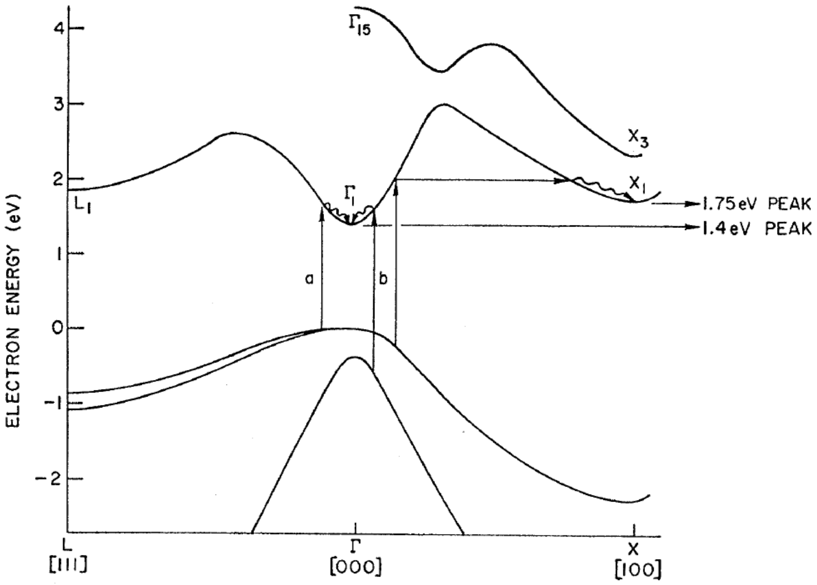
TABLE I: Results of data fitting for GaAs response time.

Wavelength (nm)	τ (ps)	Comment
860	76±26	$V_{gun} = 200$ kV
860	69±22	$V_{gun} = 250$ kV
785	11.5±1.2	$V_{gun} = 200$ kV
785	9.3±1.1	$V_{gun} = 250$ kV
710	5.8±0.5	$V_{gun} = 200$ kV
710	5.2±0.5	$V_{gun} = 250$ kV
520	$\leq$1	upper estimate placed
460	$\leq$0.14	upper estimate placed

GaAsP at 520 nm



P concentration 45%

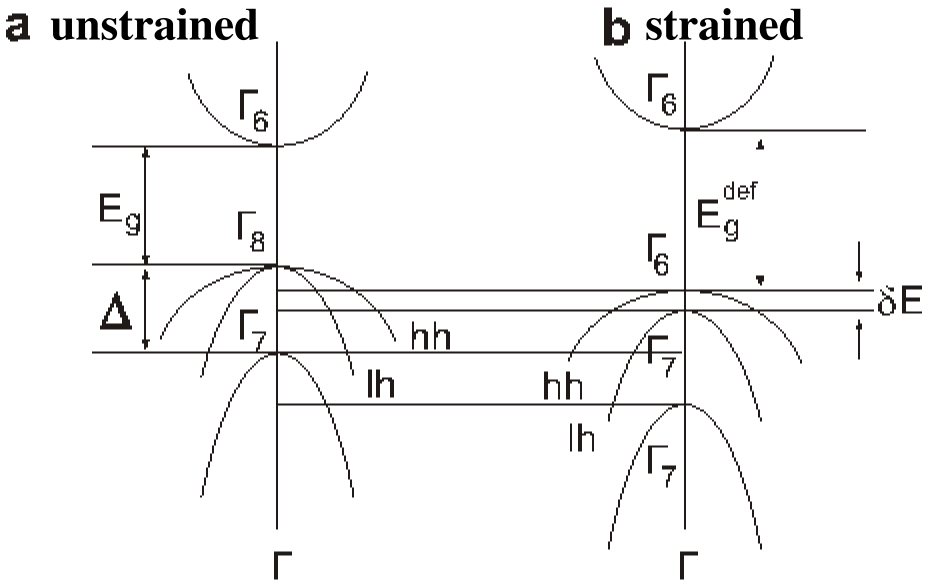


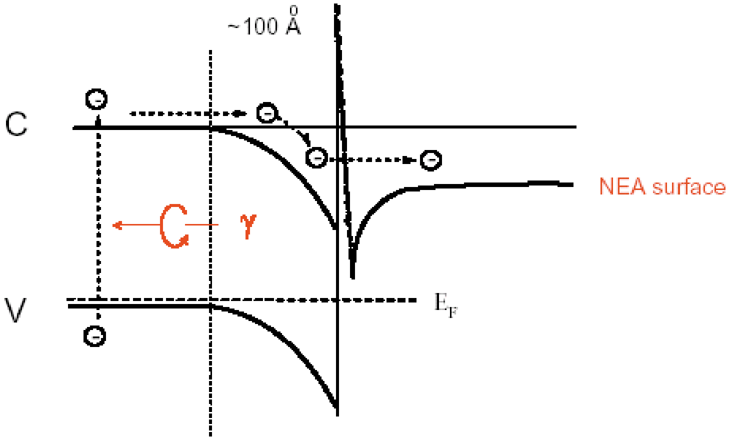
Polarized photoelectrons

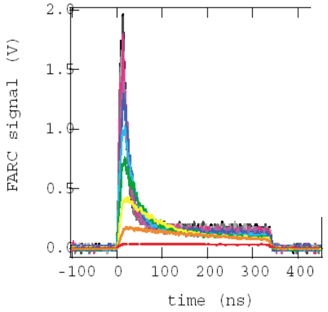
In strained GaAs, spin degeneracy of two states ($\Gamma_{6,7}$) is removed.

Circularly polarized light of the right wavelength produces polarized electrons (> 80% polarization measured). Low QE.

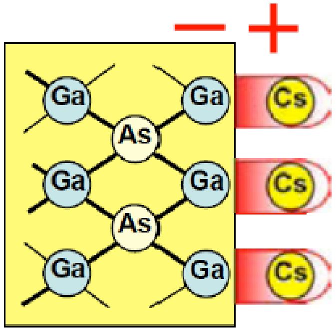
Doping is important to increase carrier density to avoid a so-called surface charge limit.



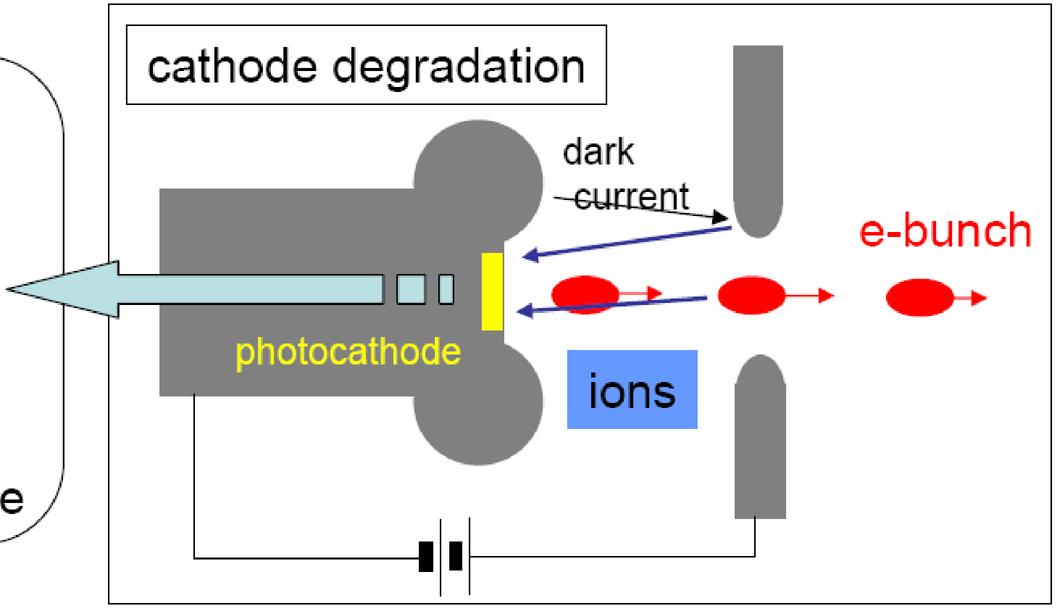




Cathode lifetime



re-cesiation recovers Q.E.
→ damage is only at the surface



- collision, deposition of residual gases
- dark current (and its enhancement)
- ion back bombardment

existing guns

CEBAF polarized gun（100kV, 0.1mA）

life ~ 2 x 10^5 C/cm^2

JLAB-ERL gun（350kV, 9mA）

life ~ 2 x 10^3 C/cm^2

improvement is required

ERL-LS

life ~ 10^6 C/cm^2

100mA / ϕ2mm、100 hours