Electron Emission and Near Cathode Effects Lecture 3

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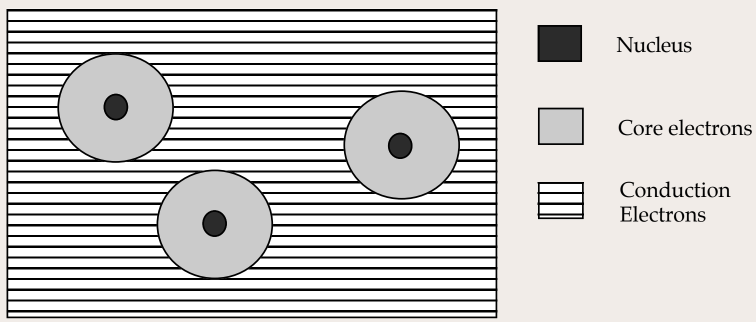
Emission processes

- Thermionic emission
- Field emission
- Photoemission
- Spin polarization
- “Bulk” effects limiting emission
- Look at microscopic mechanisms…

Microscopic models: Metals

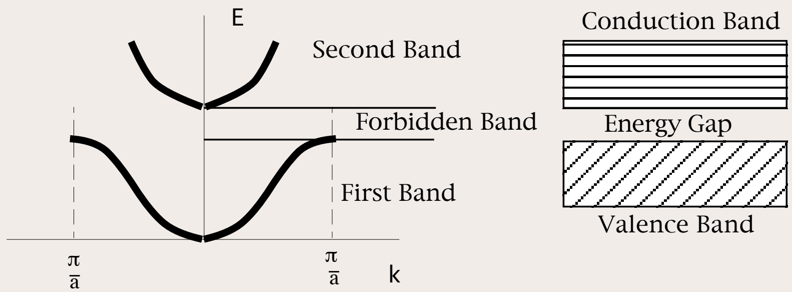


DRUDE'S MODEL OF AN ELECTRON "GAS"

- In a metallic crystal lattice the outer electrons, *valence electrons*, orbits overlap and are shared by all the atoms in the solid.
- These electrons are not bound and are free to conduct current, typically the free electron density in a metal is 10^{23} cm^{-3}. They form a plasma gas.

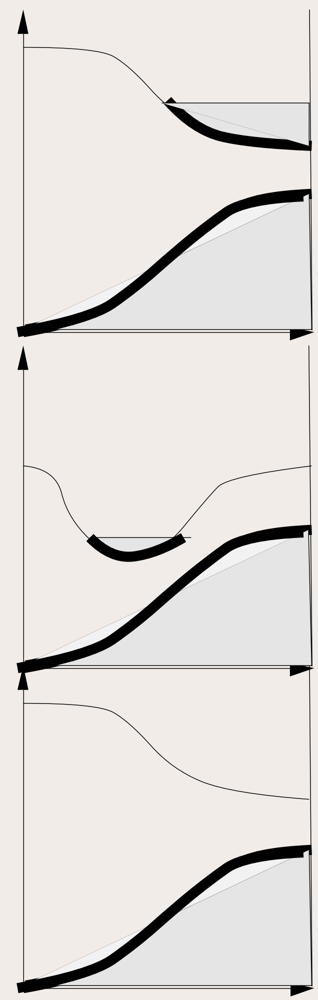
Microscopic Models: Semiconductors

- In a semiconductor such as GaAs the valence electrons are bound in covalent bonds.
- At low temperatures the electrons are all bound but at higher temperatures or with doping they are liberated to contribute to current conduction.
- A semiconductor acts like an insulator at low temperatures and a conductor at high temperatures.



Band structure diagrams

- A material's internal structure dictates its electronic characteristics
- This is displayed by Brillouin diagrams (*U*-*k*)
- Three distinct possibilities



Metal Because of electron Concetration

Metal or semi-metal because of band overlap

Insulator for Egap~8eV
Semiconductor for Egap~1eV

Density of states and Fermi energy

- In solid, one has at low temperature, a "sea" of electrons forming a sphere in *k*-space. This surface is at the *Fermi energy*,

$$E_f = \frac{\hbar^2}{2m} k_f^2 = \frac{\hbar^2}{2m}\left(3\pi^2 \frac{N}{V}\right)^{2/3}$$

- Density of states is obtained by differentiating N by E

$$D(E) \equiv \frac{dN}{dE} = \frac{V}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\sqrt{E} = \frac{4\pi(2m)^{3/2}}{h^3}\sqrt{E}$$

- In Fermi-Dirac statistics, the energy levels are populated as

$$f(E) = \frac{1}{e^{(E-E_f)/KT}+1}$$

- To calculate emission one must sum relevant electrons as

$$dN = D(E)f(E)dE$$

Thermionic emission

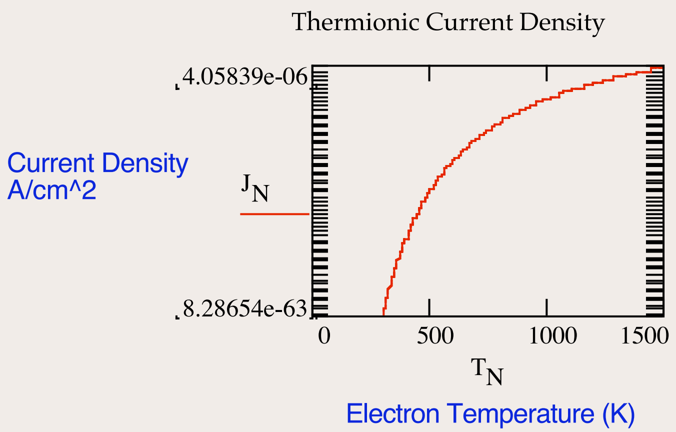
- The *work function W* is defined as the distance from the Fermi energy to the potential of the metal ϕ_m
- To calculate the thermionic current, one must sum only the electrons going in the right direction (x). Flux:

$$I = A\int qv_x dN = \int_{E_f+q\phi_m}^{\infty} \frac{4A\pi q(2m)^{3/2}}{h^3} v_x \sqrt{E} e^{-(E-E_f)/KT} dE$$

- Integrate to obtain the *Richardson-Dushman* eqn.

$$I \propto AT^2 \exp\left(\frac{-q\phi_m}{KT}\right)$$

Enhanced emission from heating



Calculation for Cu

- At room temperature, there is no thermionic current for metals
- At high temperature (>1000 K) there is notable current
- Metalloids (LaB_6, etc) have much better performance
- Applications of strong fields helps!

The Schottky Effect

- Application of external fields lowers work function (barrier suppression)

$$\exp\left(\frac{-q\phi_m}{KT}\right) \Rightarrow \exp\left(\frac{-q\left[\phi_m - V_{external}\right]}{KT}\right)$$

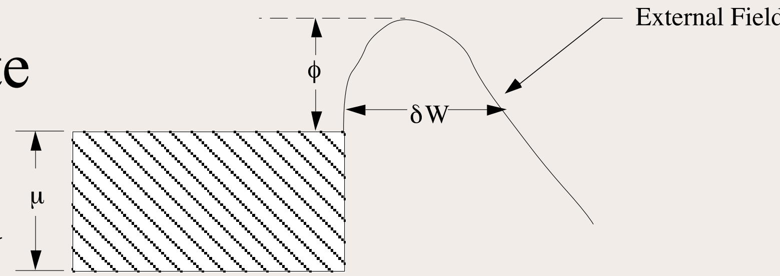
$$I_S \propto AT^2 \exp\left(\frac{-q\left[\phi_m - V_{external}\right]}{KT}\right)$$

- Schottky enhancement factor

$$I_S = I_0 \exp\left(\frac{qV_{external}}{KT}\right)$$

Field (cold) emission

- The Schottky effect is accompanied by quantum tunneling, because of the finite width of the barrier
- These effects are summarized in the Fowler-Nordheim relation *(E* is the electric field):



$$I_F = 6.2 \times 10^6 \frac{(\mu/\phi)^{1/2}}{\alpha^2(\phi+\mu)} E^2 \exp(-6.8 \times 10^7 \phi^{3/2} \alpha / E)$$

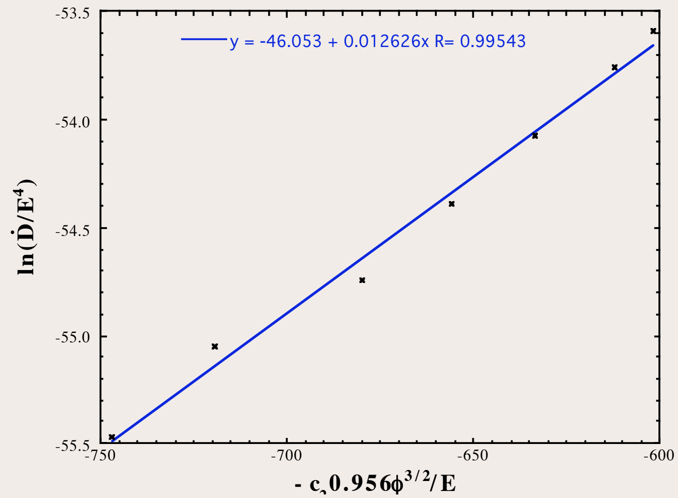
- This is a very fast function of *E!*
- One also introduces *ad hoc* field enhancement factor β

Measurement of β

- Fit electron emission current to electric field (Fowler-Nordheim plot)
- Fit radiation from RF cavities to Fowler-Nordheim

$$\overset{\circ}{D} \propto J(\beta E_p)E_p^2 \propto \beta E_p^4 \exp\left[-c_2\phi^{3/2}\left[\frac{0.956}{\beta E_p} - \frac{1.06c_3^2}{\phi^2}\right]\right]$$

- Enhancement always very large (>40)



Data from UCLA RF gun

Photoemission in metals

- Photoemission occurs for metals when the photon energy excedes the work function $h\nu > W$ = 4.5 eV in Cu.
- For very high photon intensity, multiphoton effects may occur, emission with $nh\nu > W$
- Field enhancement from Schottky barrier lowering is

$$I = I_0 \exp((h\nu - W)^2) \propto (h\nu - W)^2$$

- Useful in high field RF photoinjectors!
- Quantum efficiency (QE)

$$\eta = N_{e-} / N_{ph} = N_{e-} h\nu / U_{laser}$$

is low ($<10^{-3}$) because of electron-electron scattering in conduction band

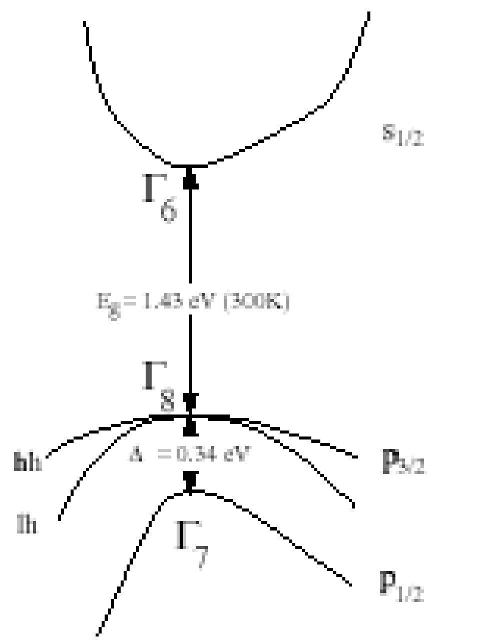
  - Electrons lose 1/2 of their energy on average in collision
  - Low QE gives risk of laser-surface damage for desired charge.

Photoemission in semiconductors

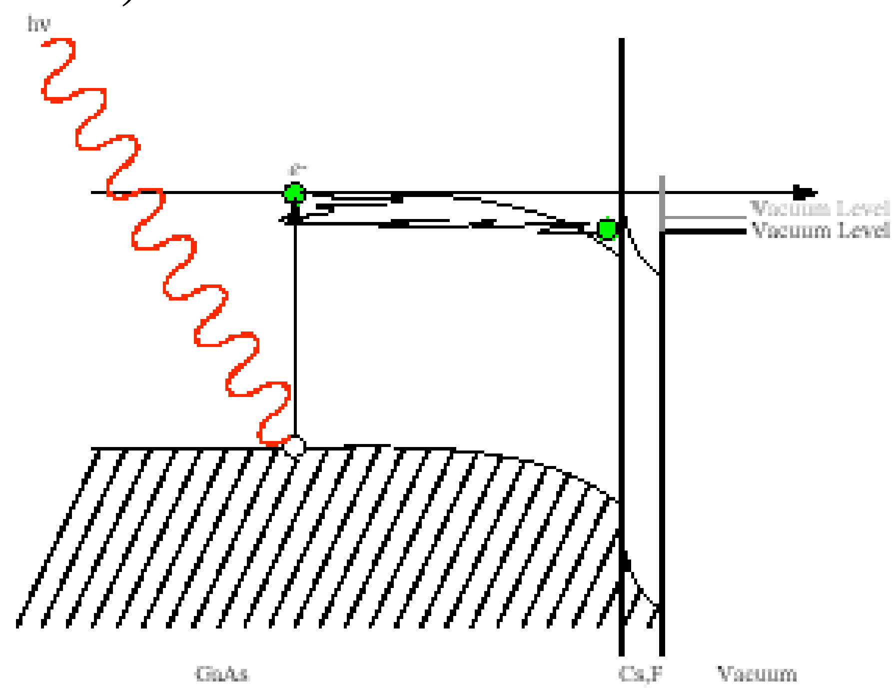
- Cesiated surfaces good
  - Negative electron affinity (NEA)
  - CsKSb (high QE at 500 nm illumination!)
  - Cs_2Te
- Very high QE possible because scattering is electron-phonon in semiconductor
- High spin polarization from strained lattices

Polarized electron emission from strained GaAs cathode

>80% polarization obtained; beats NLC requirments
Low photon energy! (<1.5 eV)

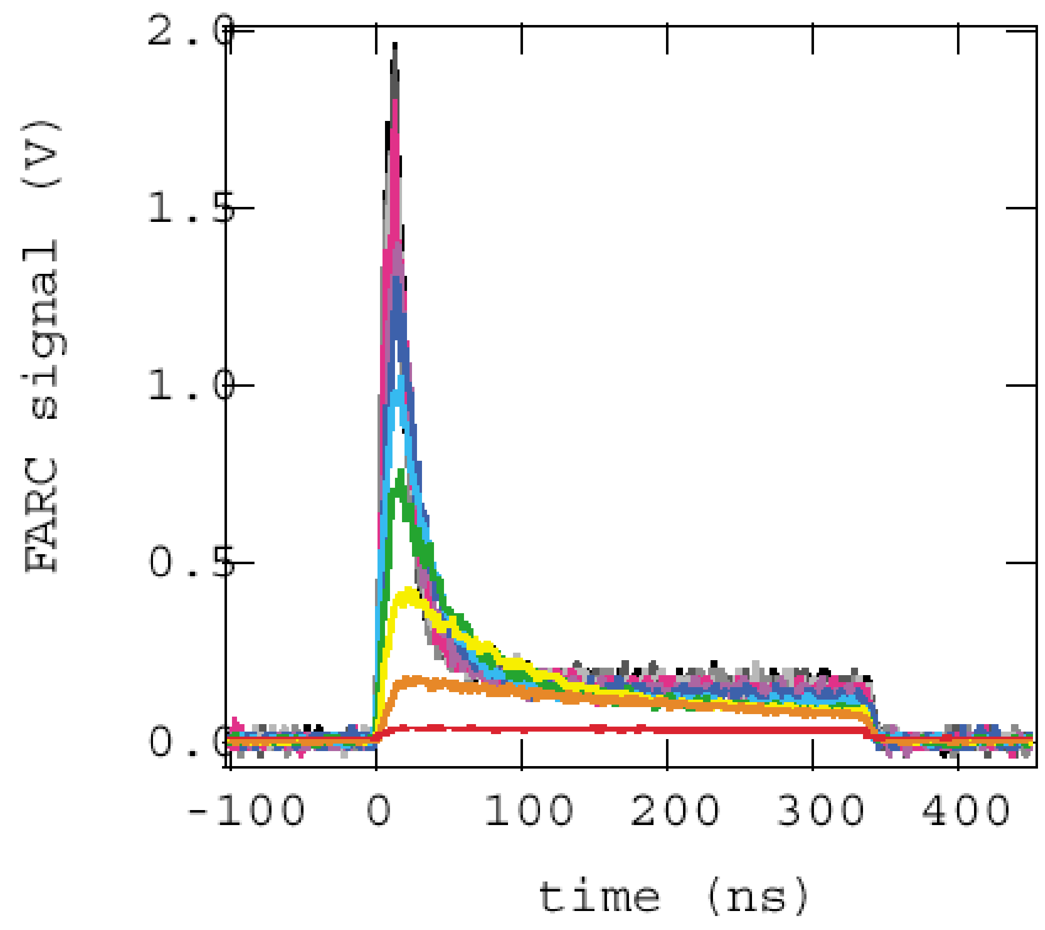


GaAs band structure in vicinity of Γ point



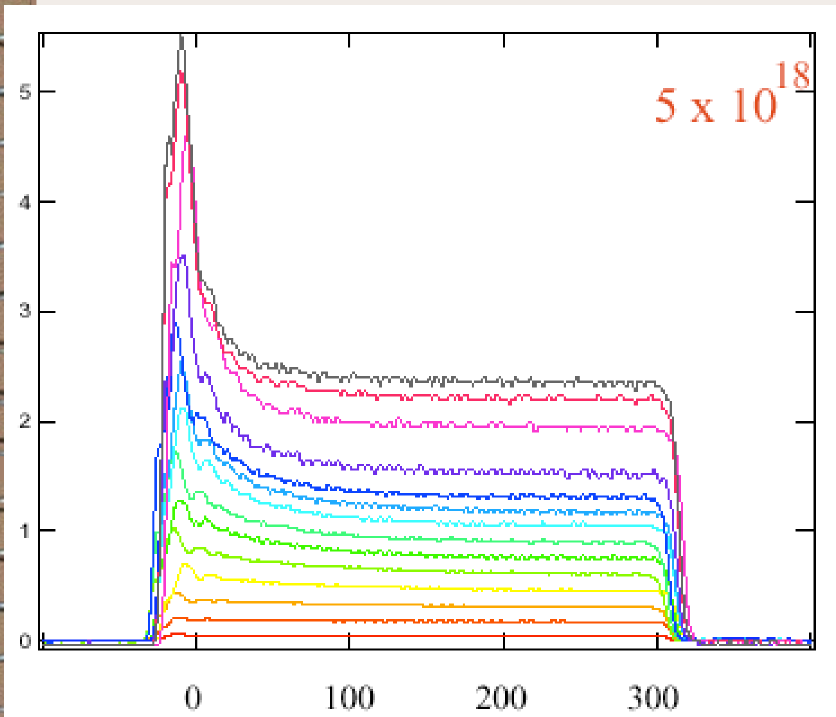
NEA Surface

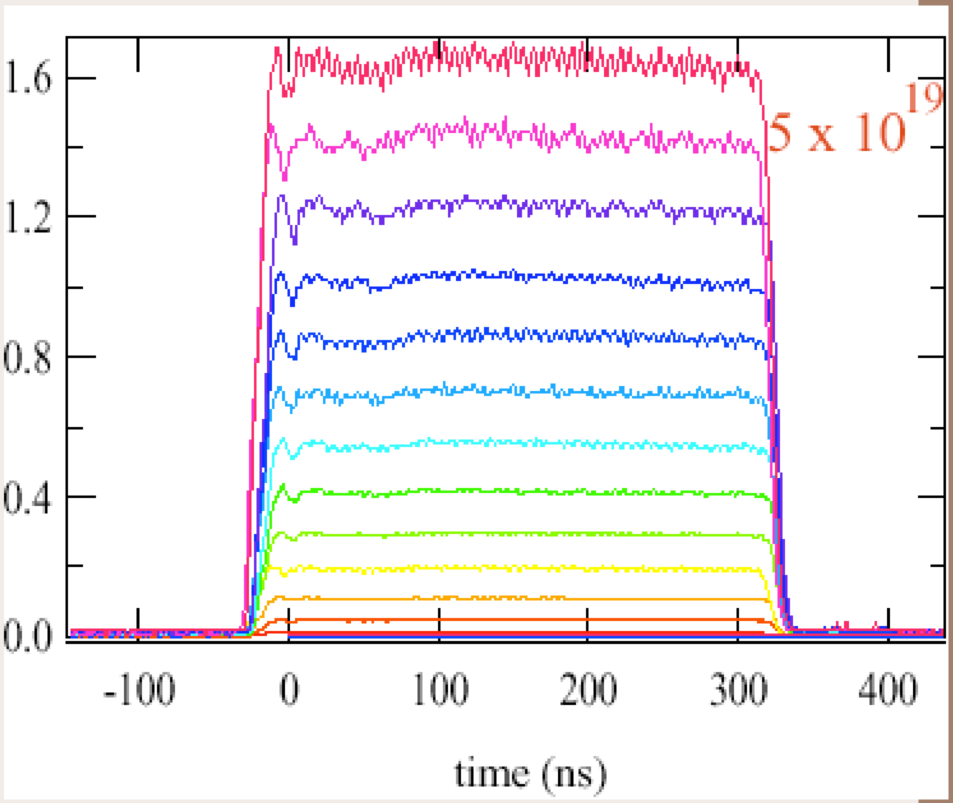
Charge limit observed from SLAC polarized electron source



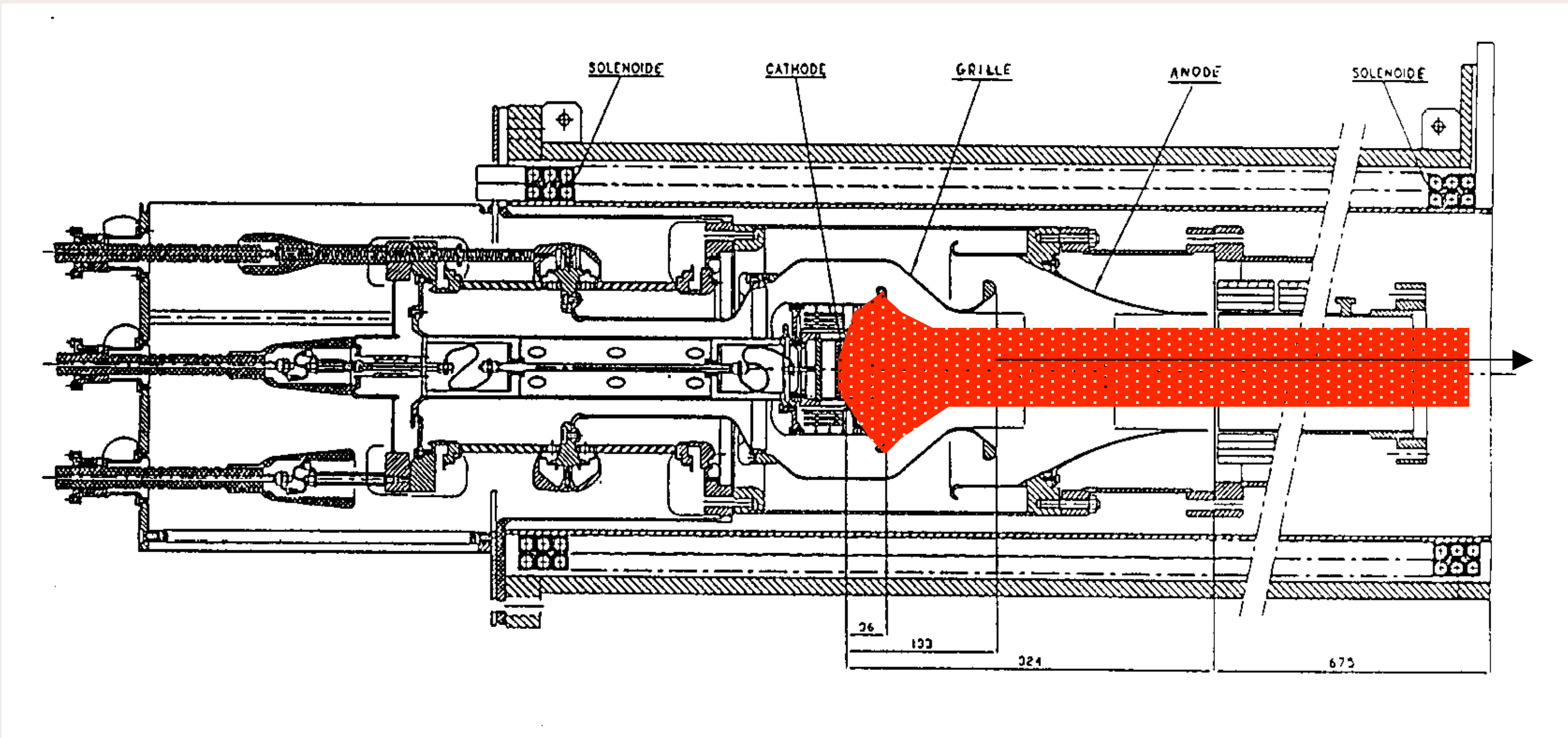
Internal space-charge effect

Enhanced doping of GaAs allows fast recovery from charge limit





DC electron source with Pierce electrode geometry



DC-field cathodes

- Switching options
  - Thermionic heating, gated voltage (klystron)
  - Photoemission
- Gated voltage problems
  - Laminar flow of current with space-charge
  - Child-Langmuir limit on current density
  - Capture of beam into RF buckets (emittance growth)