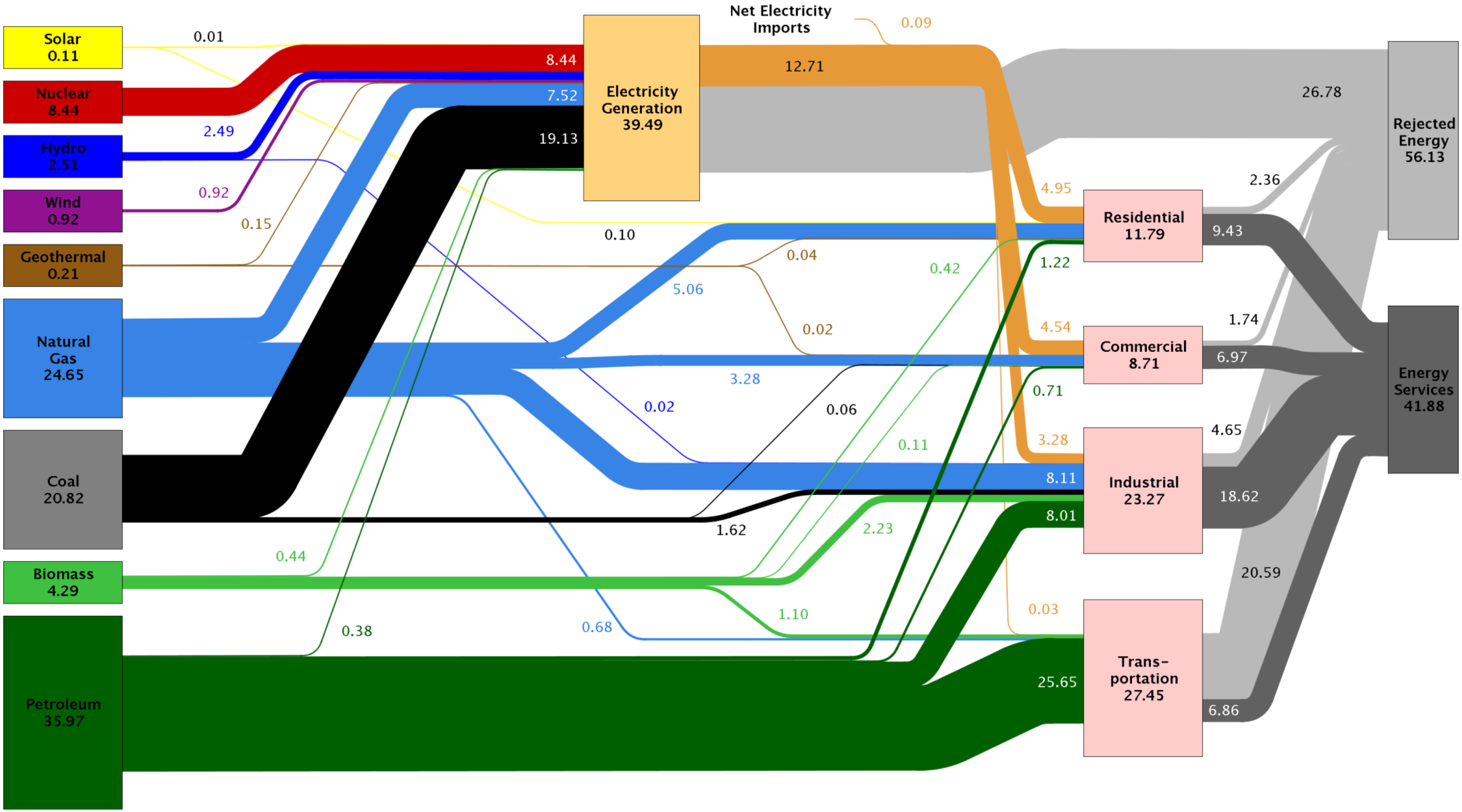
# Inverse Tunneling of Electrons in Field Emission Heat Engines

Tony Pan
Invention Science Fund
Bellevue, WA, USA

For NASA Workshop on Thermionic Energy Conversion, 2014

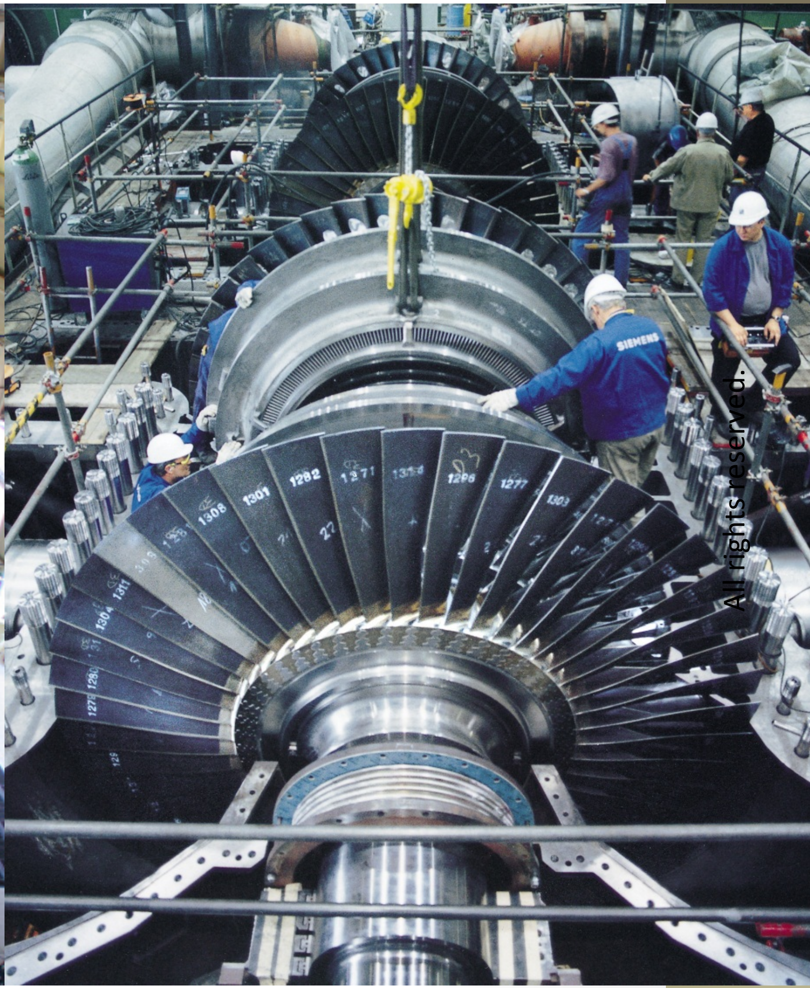
# MOTIVATION

# Estimated U.S. Energy Use in 2010: ~98.0 Quads



Source: LLNL 2011. Data is based on DOE/EIA-0384(2010), October 2011. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for hydro, wind, solar and geothermal in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." (see EIA report for explanation of change to geothermal in 2010). The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

# Steam Turbine

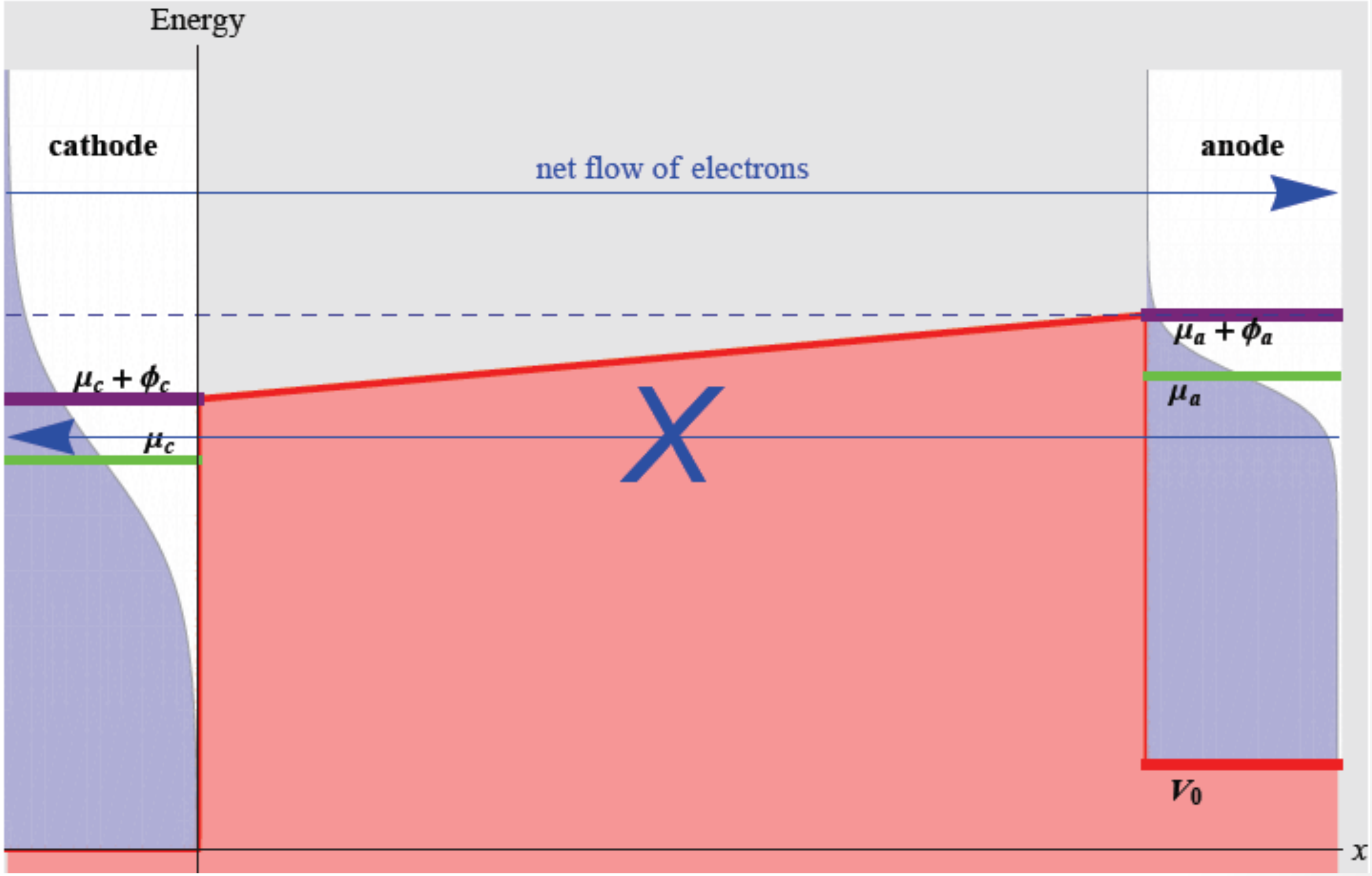


# HEAT-TO-ELECTRICITY CONVERSION: CONTEXT & MARKET SIZE

- Over past 100 years, and even today, >90% of electricity generated worldwide is via steam turbines.
  - Victorian-era tech: Burn fuel, heat steam/air, turn mechanical inductor.
- Heat engines for electrical power: >$100 Bn / yr.
  - I.e. steam turbines, gas turbines, reciprocating engines.
  - For continuous / peaking / standby / emergency power generation.
- Wanted features of a new heat-to-electricity converter:
  - Ultimate goal: < 1 $/W capital costs
  - High power density (i.e. compact.)
  - High efficiency at large and small scales, and across wide temperature spans.
    - Turbine operation limit 900K, but most ‘fuels’ can burn at 2,000K in air.
    - Turbines work very poorly under 100 kW. Mechanical engines are lousy under 10kW.
  - No moving parts.

# TECHNICAL INTRO

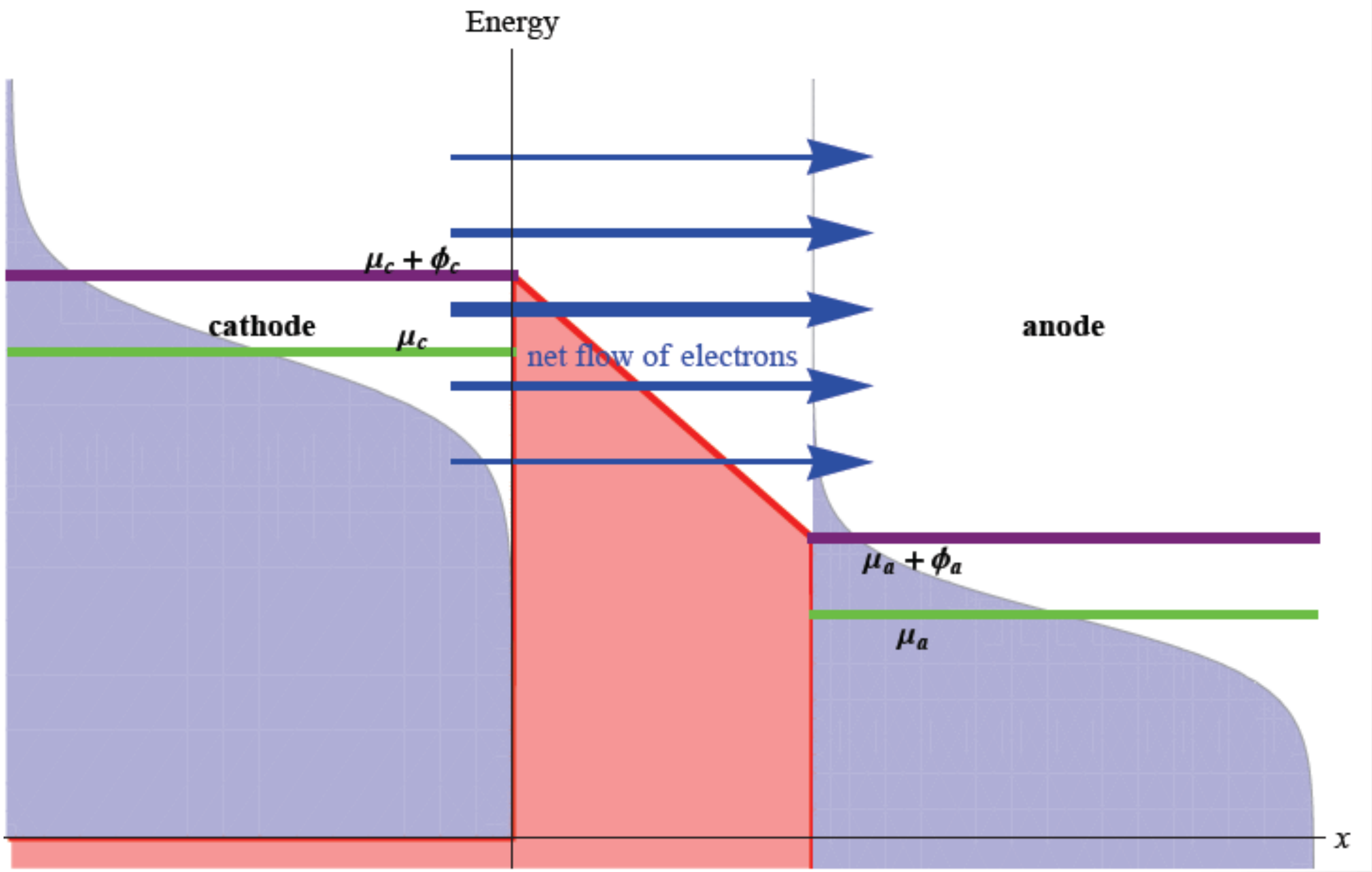
# Thermionic Converter



# Thermionic Converter

- Requires high temperatures (e.g. 1,500 - 2,000 K)
- Thermionic emission: Over the barrier
  - Emitted electron energies >> Fermi level
  - Okay current density (>1 A/$cm^2$)
    - Prefer smaller vacuum gap, 0.1mm doable
    - >$10^2$ W/$cm^3$, 100X higher than mechanical engines
  - Efficiency limited by space charge and anode work function
- Heat → Electric potential energy

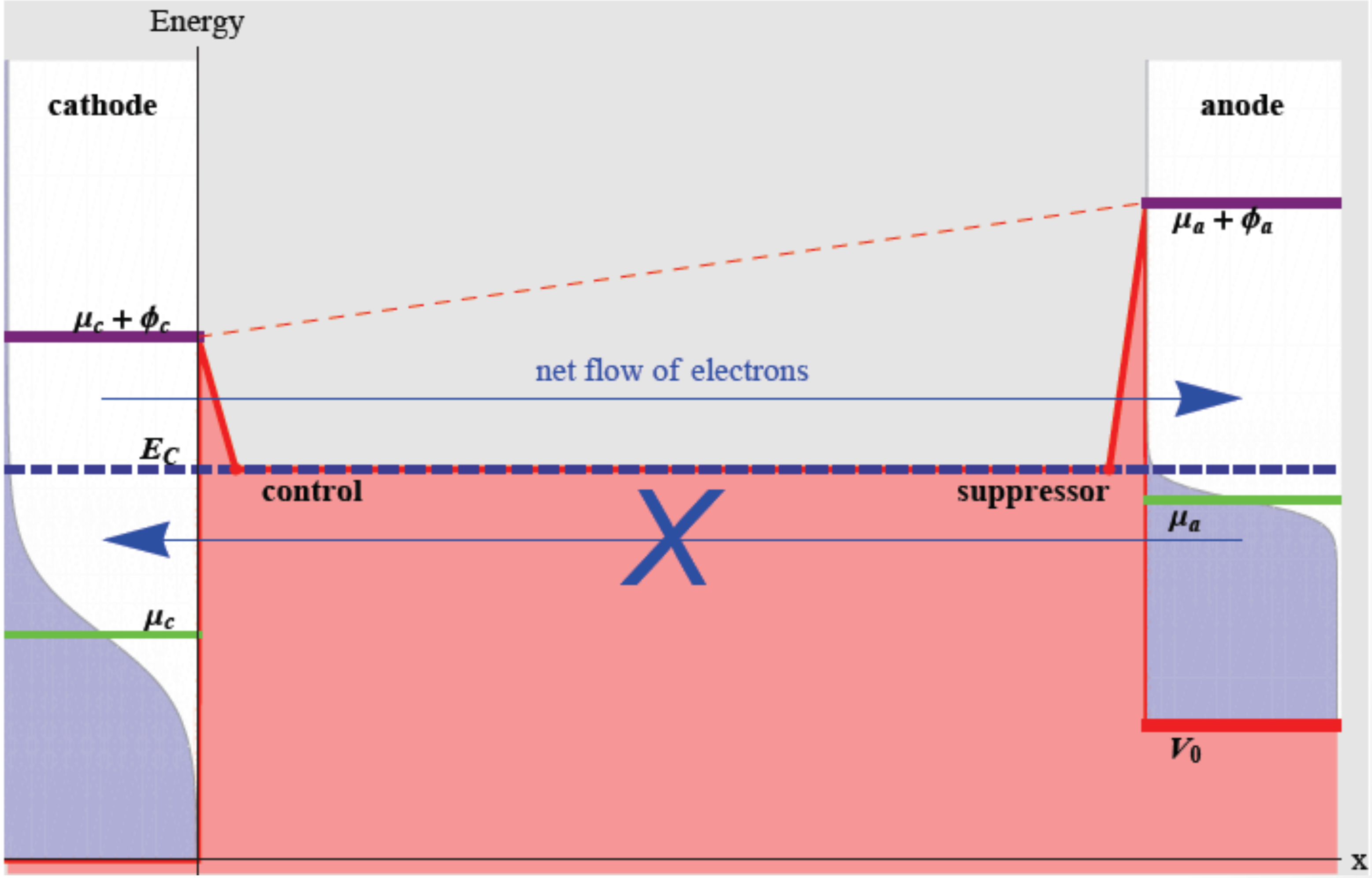
# Field Emission Diode



# Field Emission Diode

- Can operate at low temperatures (e.g. 300K)
- Field emission:  Tunnel through barrier
  - Emitted electron energies ~ Fermi level
  - High current densities $>10^7$ A/cm$^2$ (microscopically)
- Electric potential energy → Heat

# “Field Emission Heat Engines”

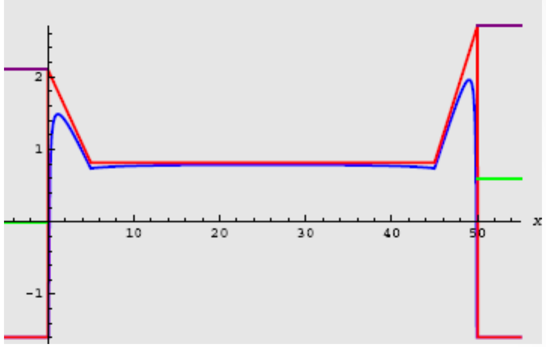


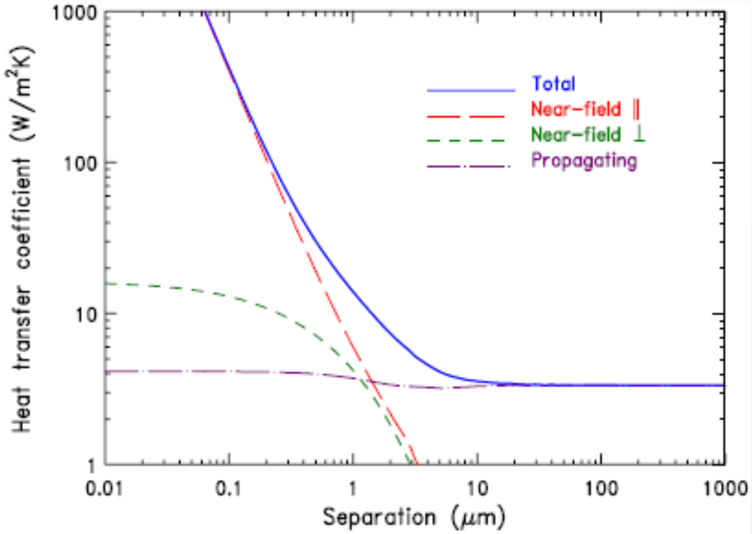
# “Field Emission Heat Engines”

- Could operate at intermediate temperatures
- Thermal-Field emission: Tunnel through barrier
  - Majority of e- energies > Fermi level, but < work function.
  - Very high current densities, up to $10^3$ A/cm$^2$ allowed
- Heat → Electric potential energy (net!)
- ‘Filtering’ of electrons based on energy
  - But NOT on ‘measurement’ (e.g. travel direction)
- ***Inverse tunneling*** of free electrons at the anode.
- Can be thought of as a thermionic converter, with *effective* work functions on anode lowered via applied electric fields.

# Theoretical Considerations

- Carnot-efficient Energy $E_C = \mu_C + V_0 / \eta^C$
- Rounded barrier from image force
- Space Charges
- Radiative heat loss
  - Evanescent-wave important @ < 1 micron
- Plasma effects
  - Two-stream instabilities





[Ottens et al., 2011, Physical Review Letters, 107, 014301]

# Modeling

- Calculate areal power density via:
    - Tsu-Esaki formalism for net current density
    - *W* is the normal electron energy
    - *N(W)* is electron supply
    - *D(W)* is tunneling probability
        - Assume rounded-triangle barrier, i.e. field-emission barrier with image force

$$J(W)dW = e[N^c(W) - N^a(W)]D(W)dW,$$

$$W = \frac{p_x^2}{2m} + V(x)$$

$$N(W)dW = \frac{4\pi mkT}{h^3}\log\left[1 + e^{-\frac{W-\mu}{kT}}\right]dW.$$

$$D(W) \approx e^{-b\frac{(\phi-W)^{\frac{3}{2}}}{F}\nu[f]}$$

- Calculate thermodynamic efficiency $\eta^{HE}$ via heat flux density *Q* at cathode/anode:

$$\eta^{HE} = \frac{V_0 \times J}{|\dot{Q}^H| + \dot{Q}_{other}}$$

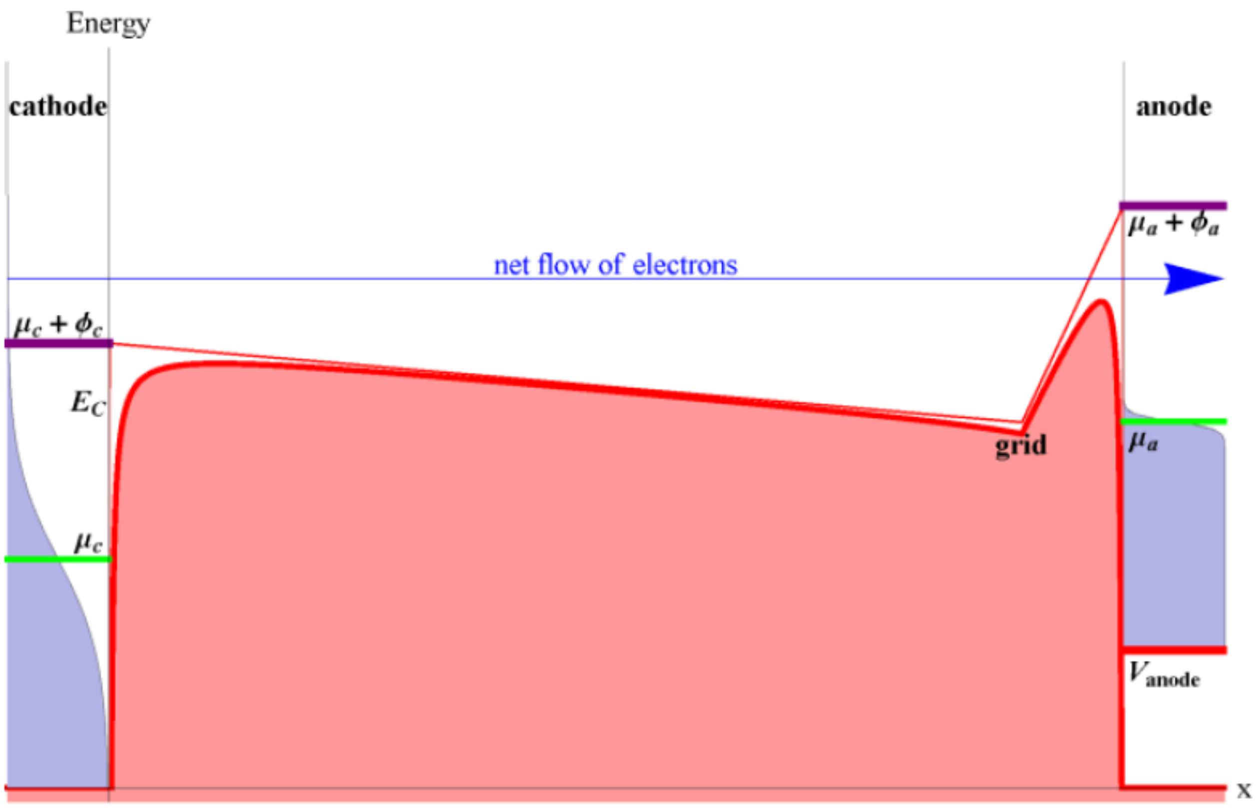
$$\begin{aligned} \dot{Q}^c &= \int_0^\infty \left[(W + kT_C - \mu_c)N^a(W) - (W + kT_H - \mu_c)N^c(W)\right] D(W)dW \\ \dot{Q}^a &= \int_0^\infty \left[(W + kT_H - \mu_a)N^c(W) - (W + kT_C - \mu_a)N^a(W)\right] D(W)dW \end{aligned}$$

- Space charges: solve Poisson's equation. Or, if there is a large voltage difference across the grids, Child-Langmuir is good approximation for max current.
- Account for radiative losses, including evanescent-wave heat transfer at small gaps.

# Grid Voltage – how large?

- The tunneling barrier is shaped by the field strength
  - So grid voltage dependent on grid-anode distance
- Schottky effect, reduction in barrier height:
  - $\sqrt{e^3/4\pi\varepsilon_0 F} \approx 1.2\ eV\ (F/1\ V/nm)^{0.5}$
  - Not hugely sensitive to field strength
    - E.g., still get >0.5 eV reduction for F ~ 0.2 V/nm
  - Lower grid voltages generally preferred
    - Less power loss per electron through grids
    - Less worry re: dielectric breakdown
    - Less need for field enhancement, more active area
    - <10 eV electrons cannot damage material
    - But: requires small grid-anode distance -> small grid wires?

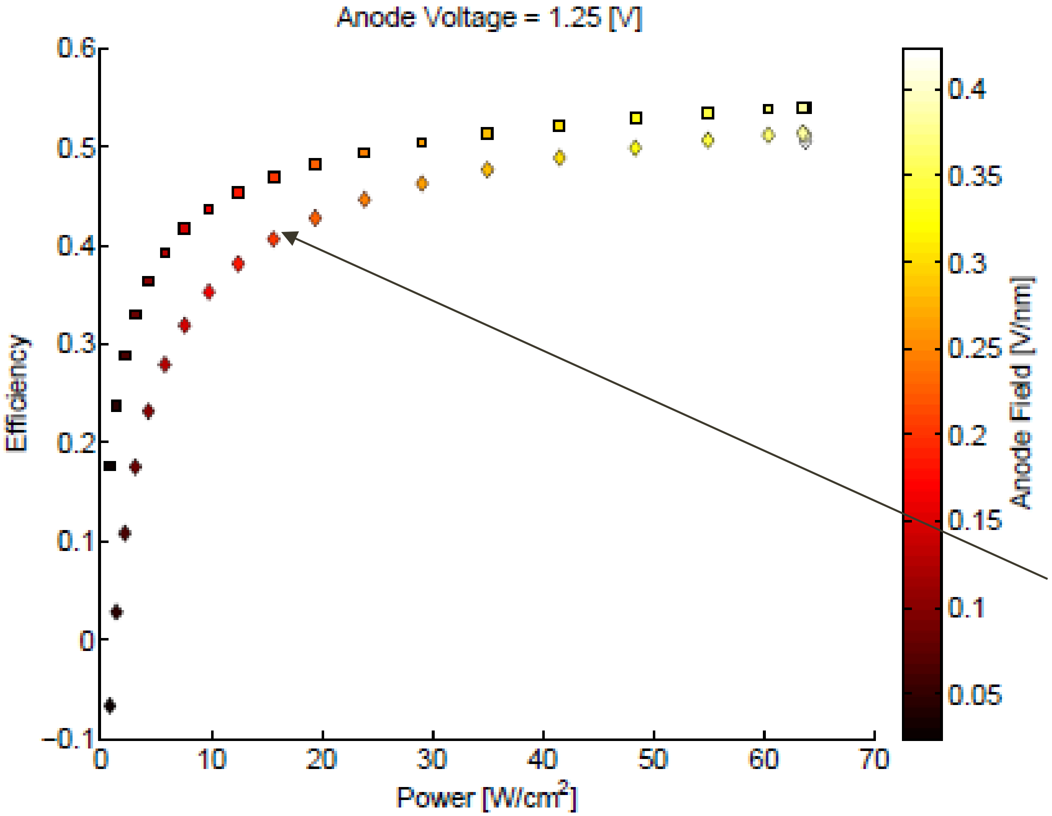
# Simplest Embodiment:
# Thermionic Cathode + Anode Grid



Simplify: classical thermionic cathode!

- Can buy 10-20 A/cm$^2$ off-the-shelf.
- Scandate cathodes reach 50 A/cm$^2$ in lab at <1,300 K. Pulsed >100 A/cm$^2$.

# Single anode-grid converter

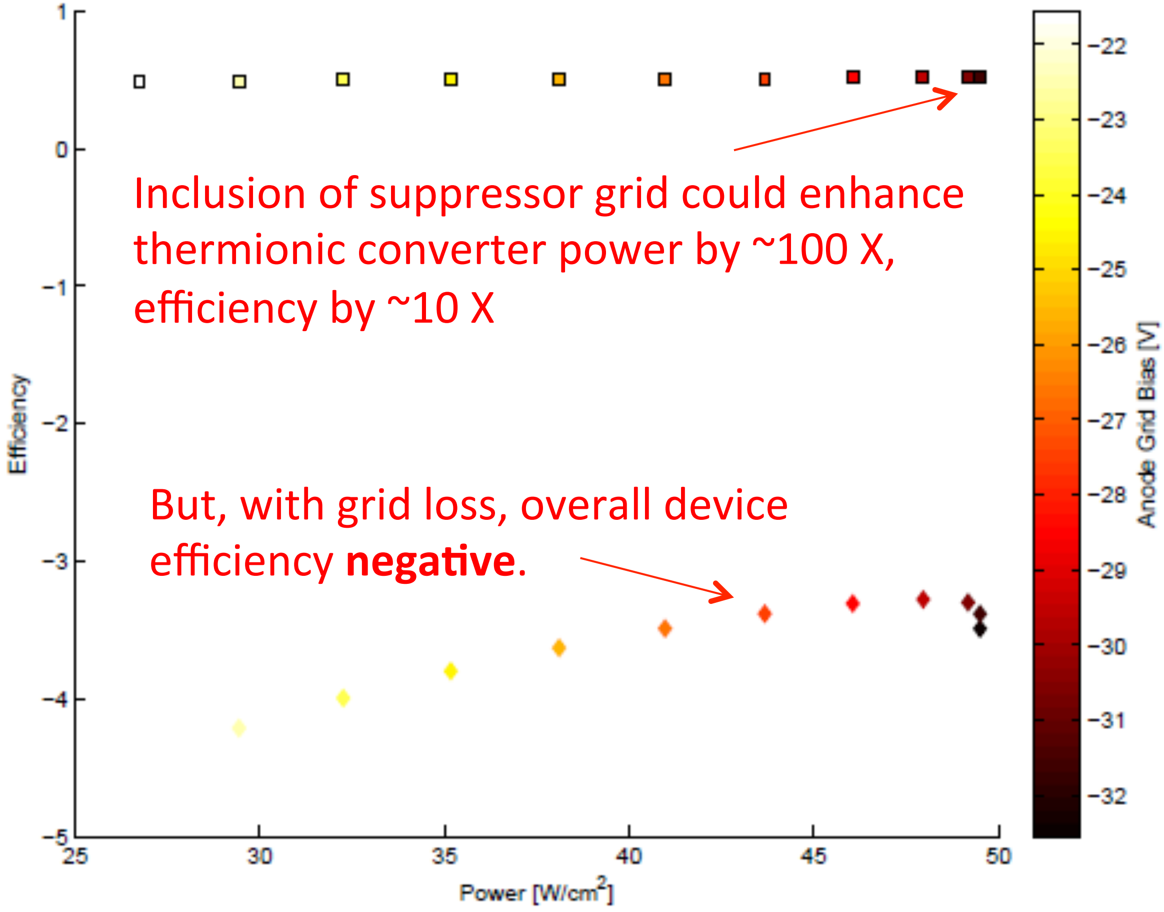


$T_H$=1,500 K, $T_C$=300 K
$\Phi_c$=2.0 eV, $\Phi_a$=1.5 eV
Varying anode E field <0.4 V/nm
Cathode-anode spacing: 10 micron

Corresponding ***classical*** thermionic converter:
Power ~ 0.3 W/cm$^2$
Efficiency ~ 7%

Bottom curve: 1% grid loss.

# GRID LOSS CAN BE DEVASTATING



Inclusion of suppressor grid could enhance thermionic converter power by ~100 X, efficiency by ~10 X

But, with grid loss, overall device efficiency **negative**.

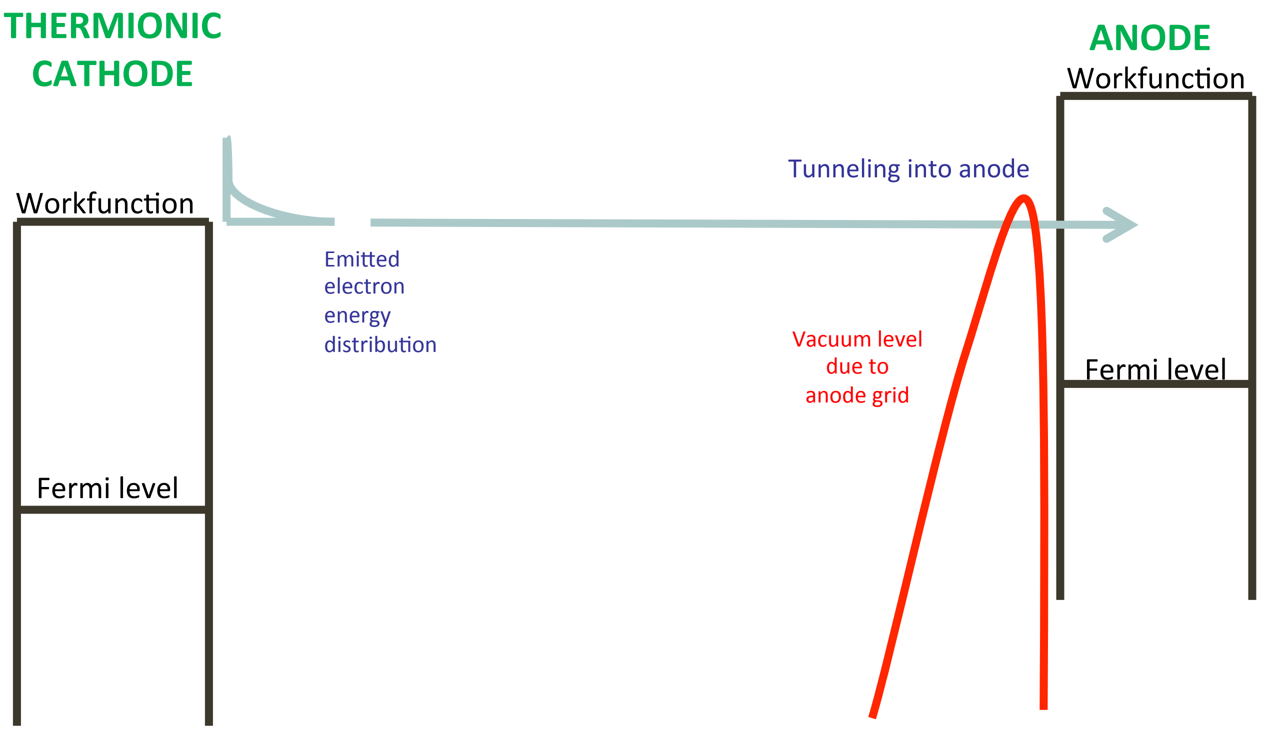
$T_C$ = 1500 °K
$\Phi_C$ = 2.0 eV
$\Phi_A$ = 1.5 eV

Grid-to-anode spacing
= 100 nm
Grid width
= 20 nm
**i.e. Grid loss = 20%**

Corresponding
**Thermionic converter**:
Power ~ 0.3 W/cm$^2$
Efficiency ~ 7%

# INVERSE TUNNELING: EXPERIMENTS

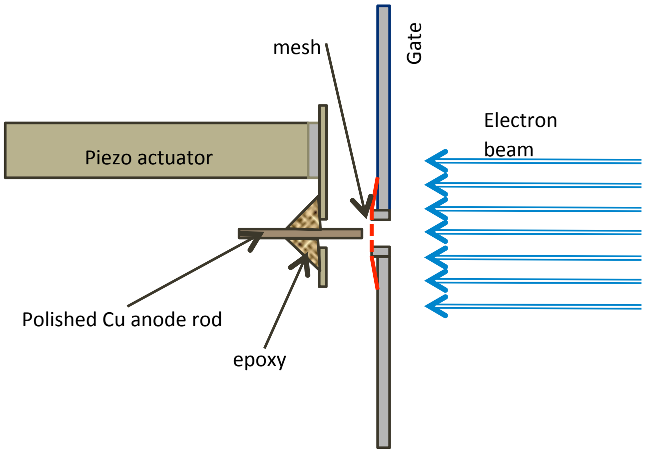
# DEMONSTRATING INVERSE TUNNELING



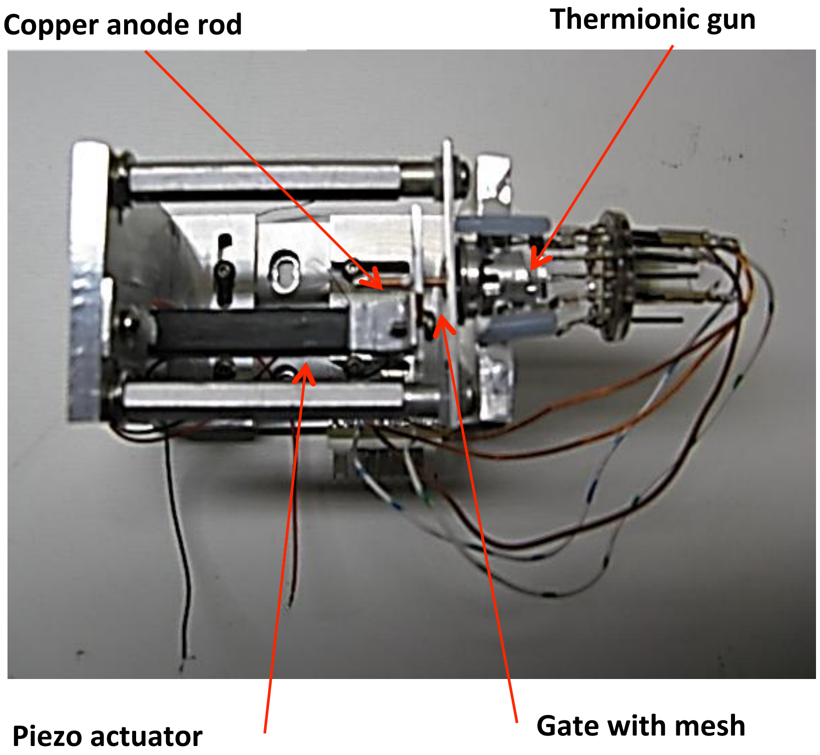
In classical physics, when the anode voltage is more negative than the stopping potential, no electrons should have sufficient kinetic energy to overcome the repulsive anode bias, *no matter what accelerating grids sit between the cathode and anode*.

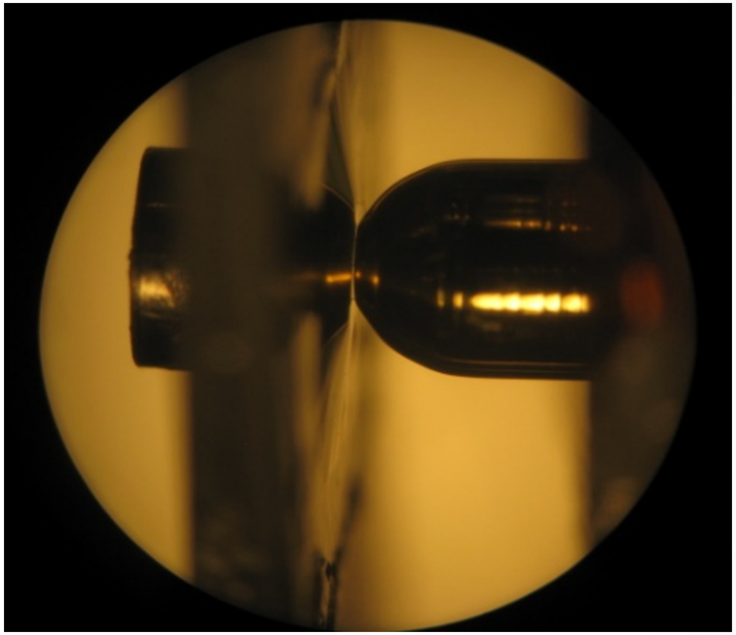
# Experiment Device

- Thermionic barium oxide cathode facing a polished brass anode, with a 2000-hole nickel mesh in between serving as the anode grid.
- Anode rod is connected to a piezoelectric actuator to reach any desired anode-to-grid spacing in situ.
- Anode and grid voltages can be independently varied.



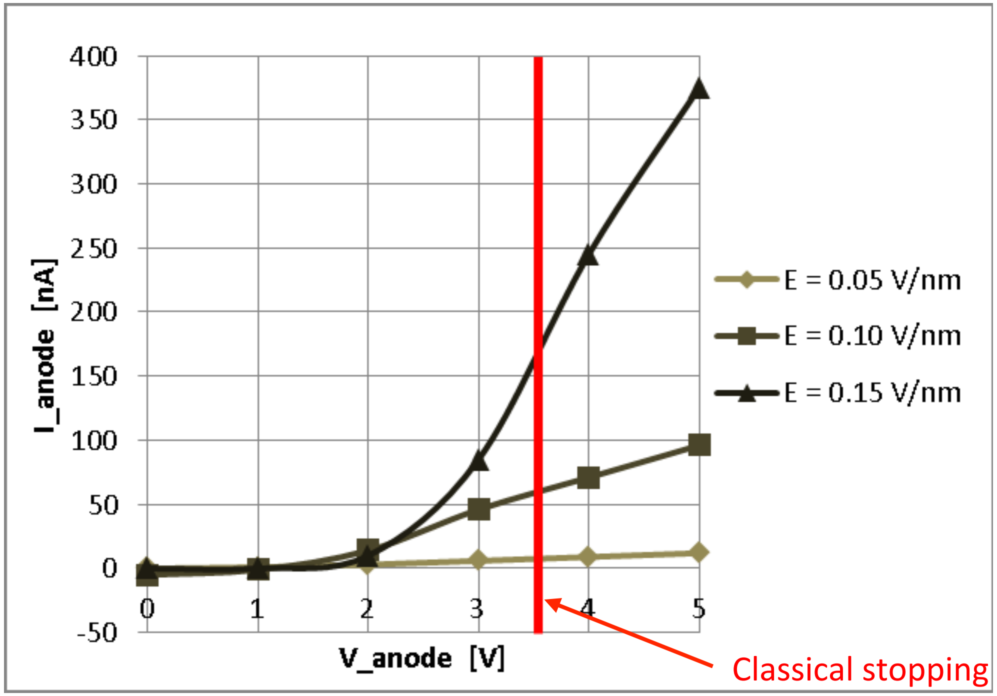
# Experiment Device





Polished brass anode with a 1mm diameter flat portion in close proximity to the stretched mesh.

# Inverse Tunneling ?



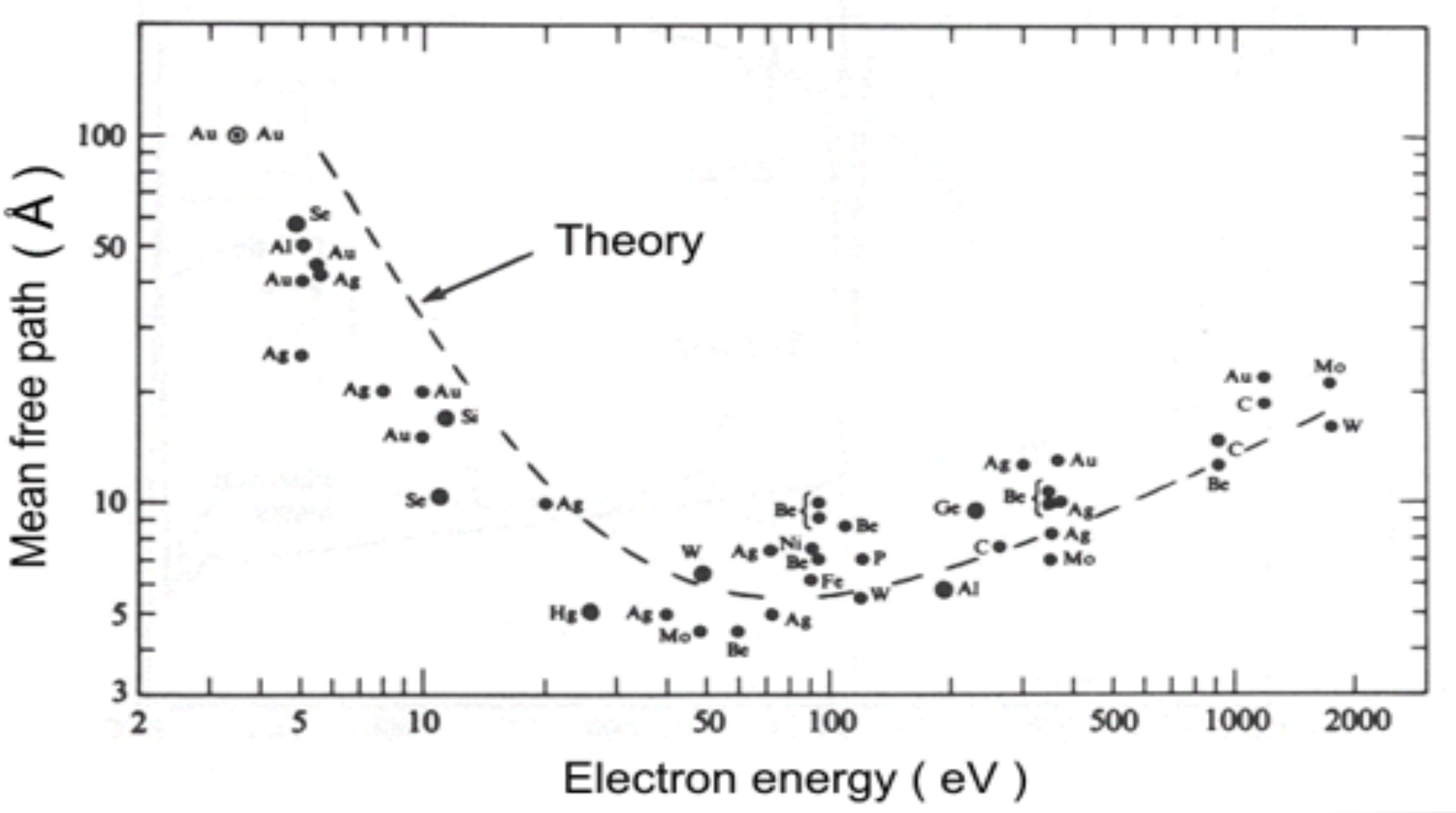
Classical stopping voltage

# Interpretation

- Most other possible contaminations to the anode current measurements have the opposite directionality of inverse tunneling.
  - Leakage current between the anode and the positive grid would decrease $I_{anode}$.
  - Field emission from the anode due to the applied field would also decrease $I_{anode}$.
- Measured anode current is proportional to the electric field strength, consistent with increased inverse tunneling probability.
- But, results are also consistent with increased current densities impinging on the anode due to classical electron optics effects driven by the positive grid.
- Nevertheless, electron optics alone should not be able to explain the non-zero anode current at anode biases more repulsive than the stopping voltage.

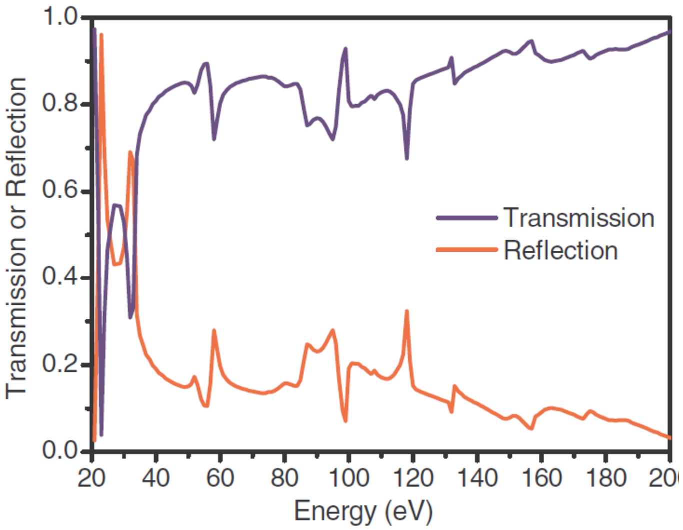
# REDUCING GRID LOSS

# Mean free path of electrons in solids

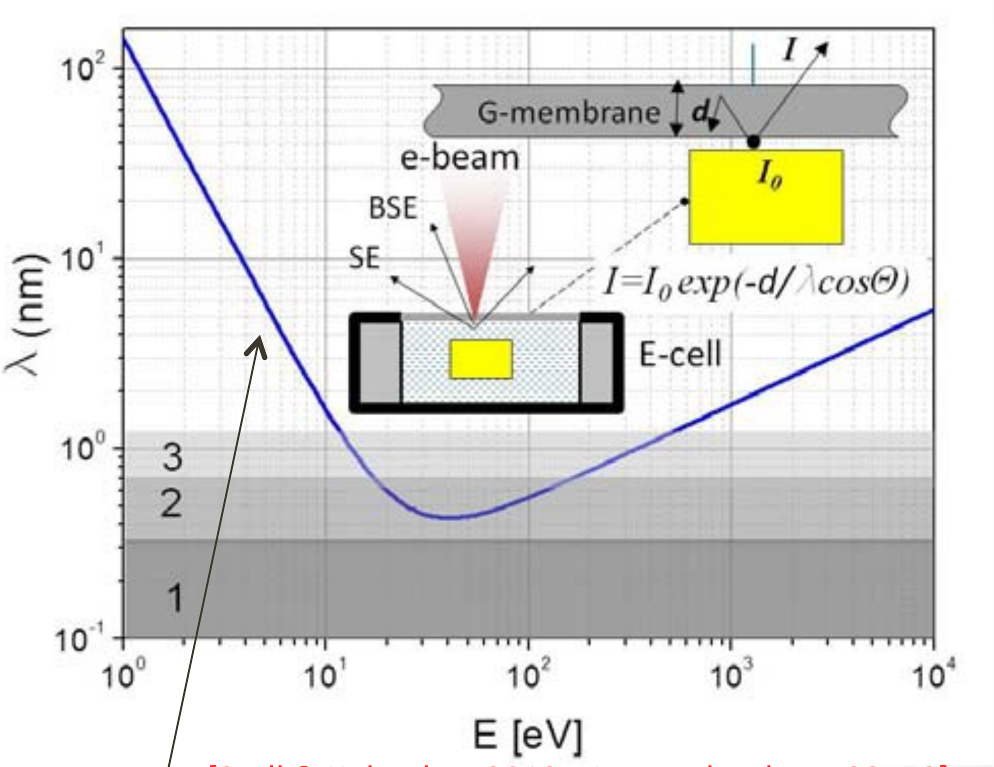


[http://users.uj.edu.pl/~ufpostaw/2_Pracownia/D1/images/jak_ba1_eng.png]

# Graphene grids



[Yan et al. 2012, Phys Rev B, 84, 224117]



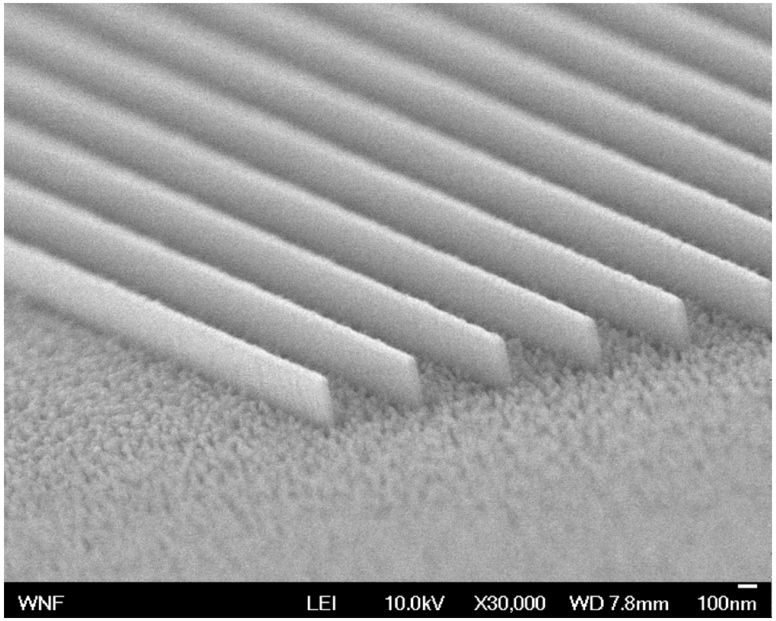
[Stoll & Kolmakov 2012, Nanotechnology, 23, 50]

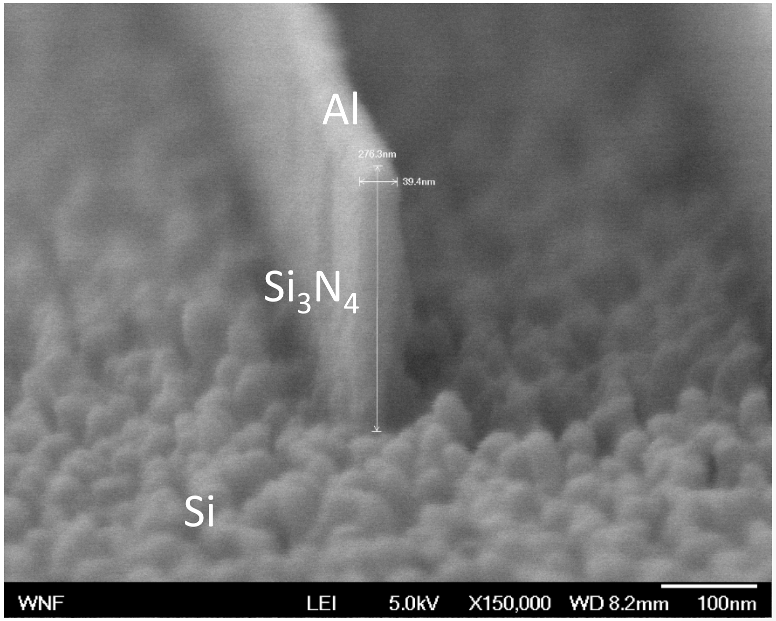
Inelastic scattering attenuation length of carbon material as function of electron energy.

For effectively 2D grids: Impinging *vacuum* electrons are unlikely to be conducted away as grid current, as most *single*-scattering events cannot reduce the electron's large normal momentum to near zero, necessary for travel in the grid plane.

# High aspect ratio grid wires feasible

- Today we can do high aspect ratio (>10:1) etches of sub-100 nm features.
- Challenge is incorporating low workfunction materials.





…and there are other ways to reduce grid loss.

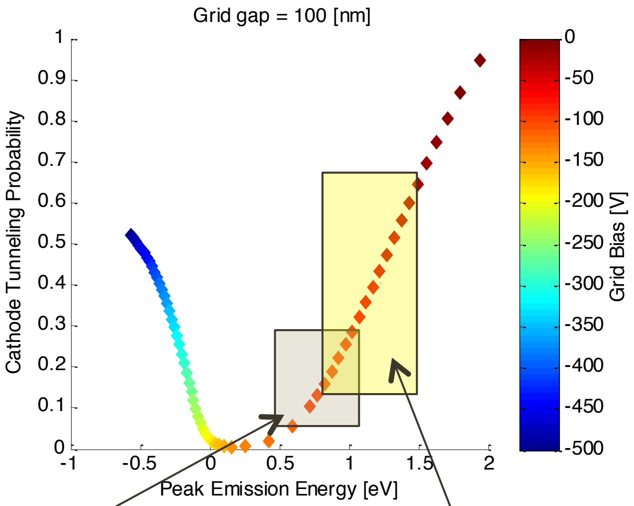
# Advertisement

- Ongoing activities
  - Sponsoring research at universities
  - Testing with commercial shops
  - Hiring for in-house development
- Areas of interest
  - Ultra low-loss grids
  - Nanofabrication (e.g. lithography) with low workfunction materials
  - Field enhancement for inverse tunneling (not tips!)
  - High current density thermionic cathodes, or Schottky cathodes with band-gap.
- If interests overlap, find me! *tonypan@gmail.com*

# APPENDIX

# WHY LARGE BIAS IS BAD

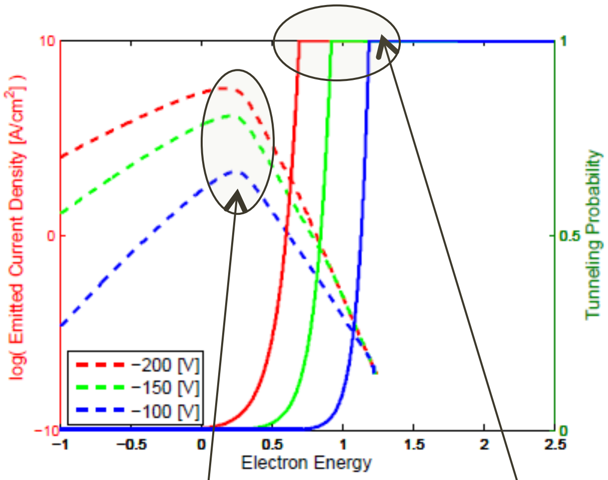
### CATHODE



*Region of "reasonable" Carnot-Efficient Energy (dependent on anode bias)*

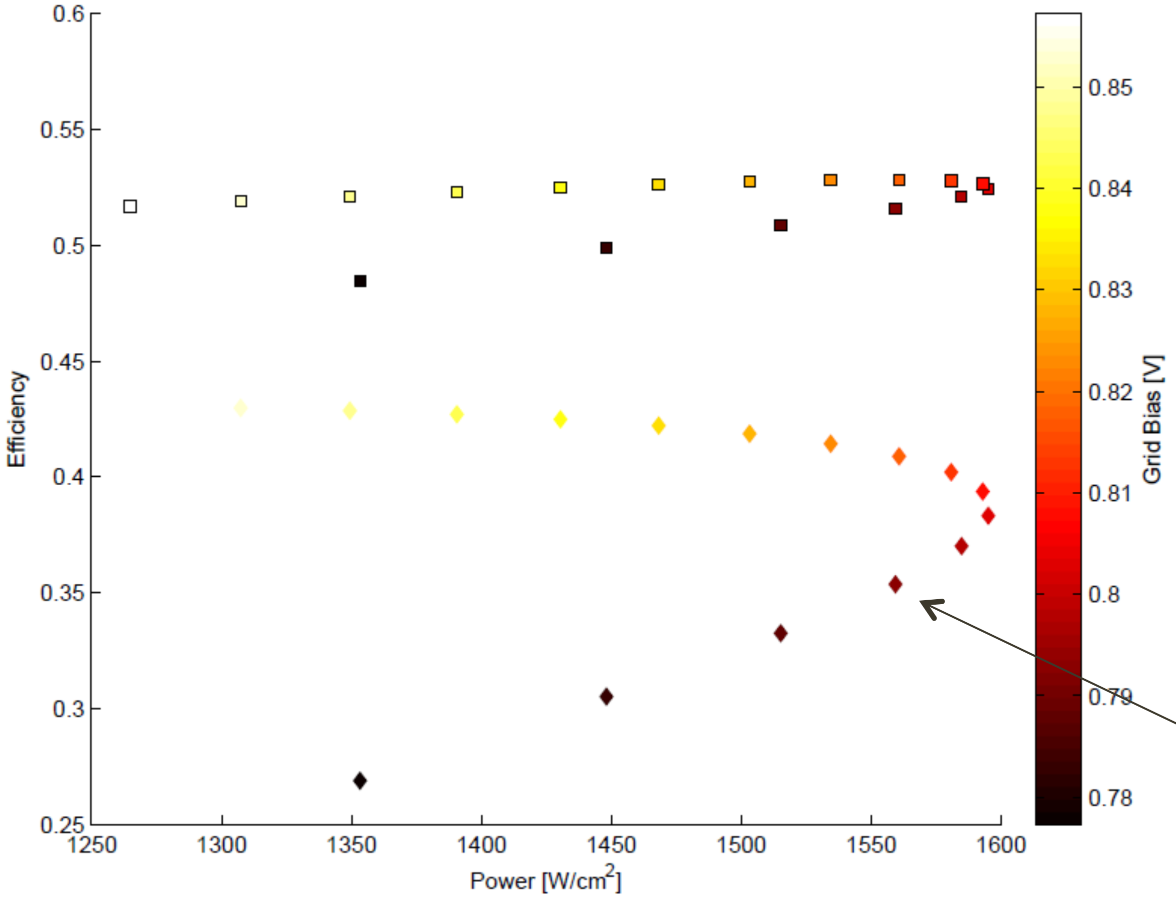
Prefer to emit slightly "hotter" electrons, to increase tunneling probability at both cathode and anode.

### ANODE



Stronger anode grid bias allows a bit more electron capture, but at the cost of <u>much</u> more anode emission (note log scale.)

# $T_H$ = 1000 K, varying grid bias



**Grid loss**

Cathode and Anode workfunctions =2.1 eV

Field strengths ~1 V/nm