Overview on Thermoelectronic Generators

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The Team

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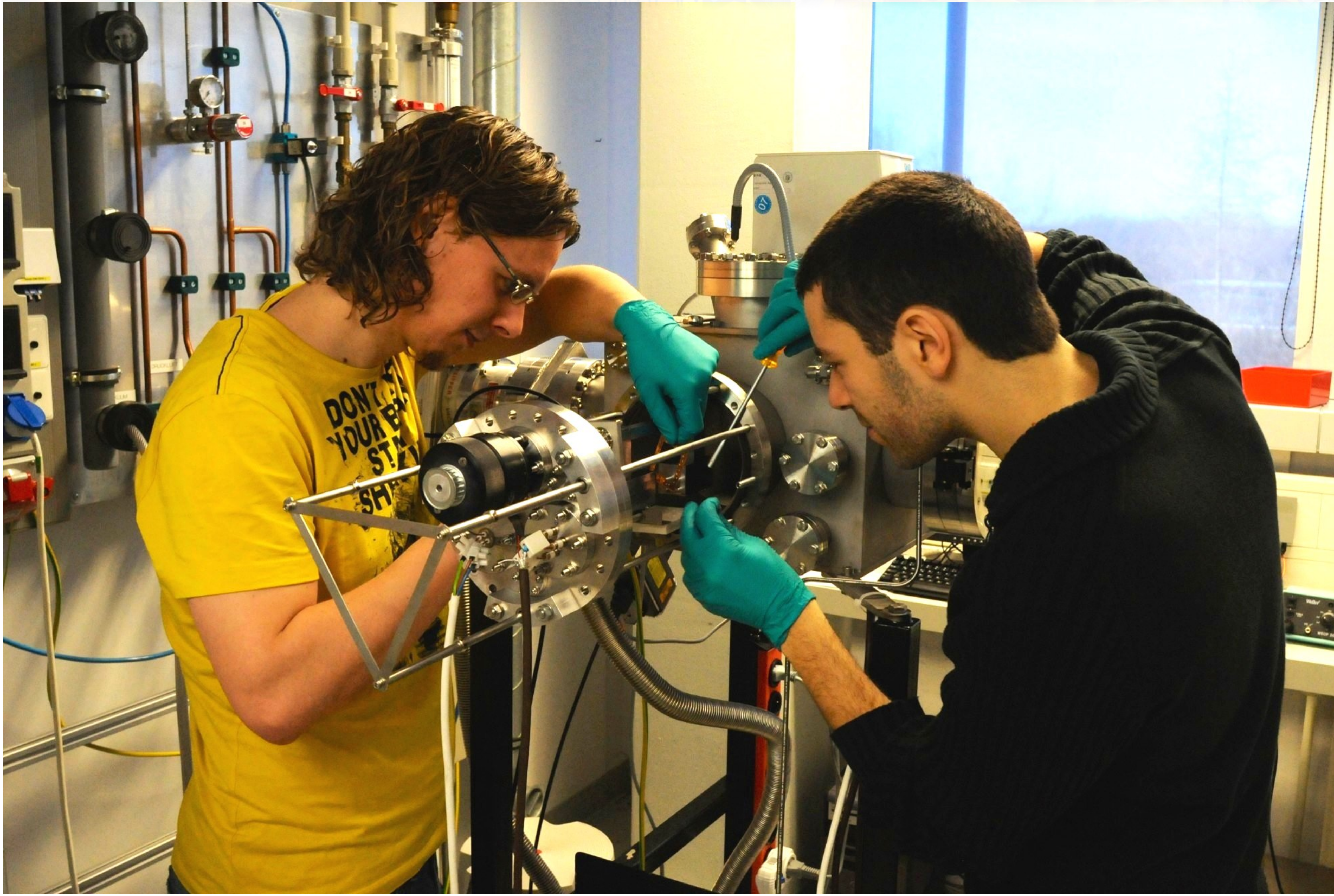

The Historical Origin of Thermionics

Use of thermionic emission to generate electric power: proposal and first studies

Hermann Theodor Simon
(1870-1918)

Regarding its impact on life ...,
science of energy is the most reliable
and seminal of all sciences.
(1918)

The Historical Origin of Thermionics

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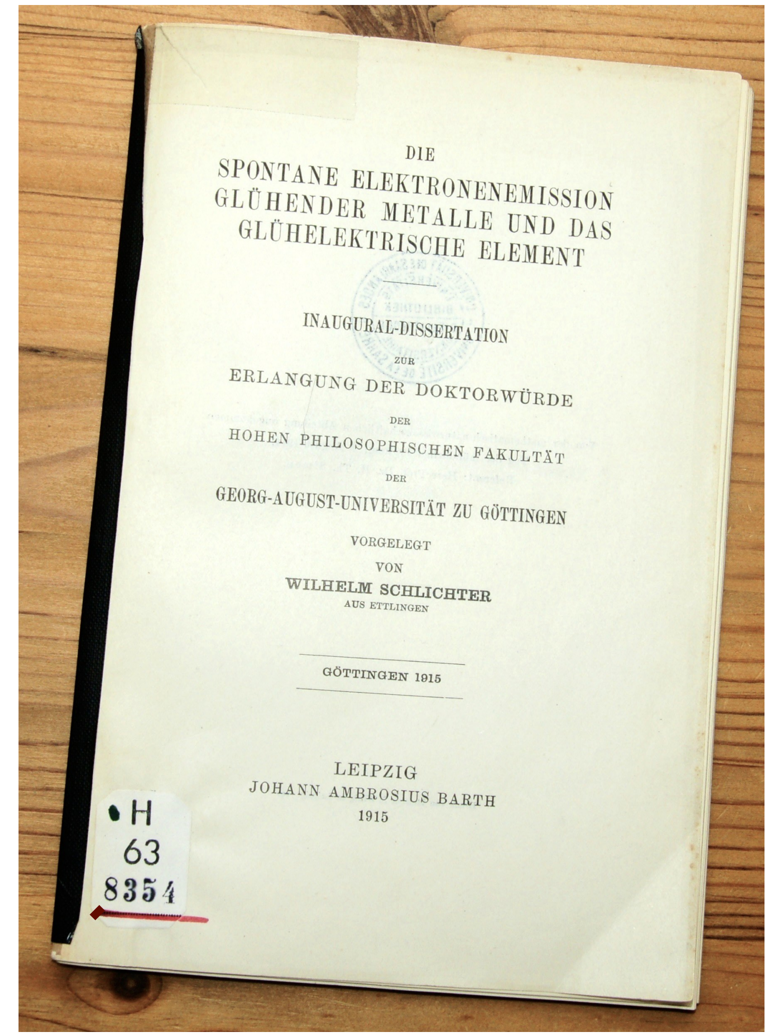


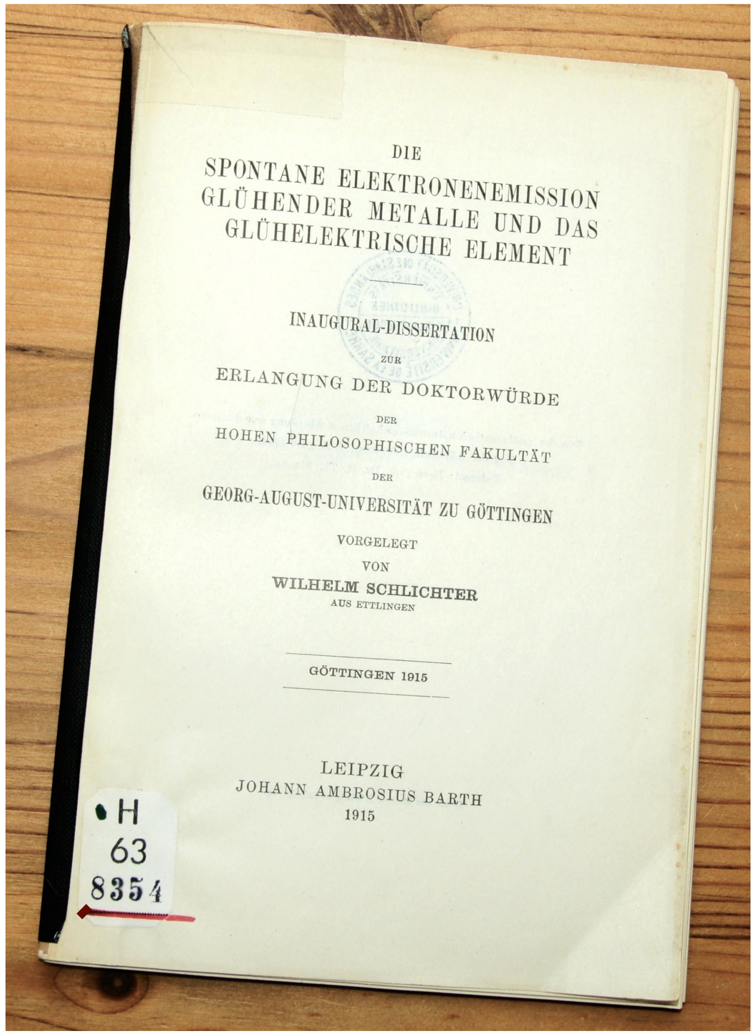
Thesis of Wilhelm Schlichter
(defense: August 2, 1914)

The Historical Origin of Thermionics

Use of thermionic emission to generate electric power: proposal and first studies

Results:

- Pt is unsuitable cathode material
- radiation loss is the main problem
- **´glow-electric elements´ can be economically feasible**



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Concepts to Solve the Space Charge Problem

1) **Neutralization** of space charge by positive ions (Cs^+)

   practical (TOPAZ), but **reduced efficiency, complex**

2) ***d_{EC}* ~ 1-3 µm** (see, *e.g.*, J.-H. Lee *et al,* APL **100**, 173904 (2012))

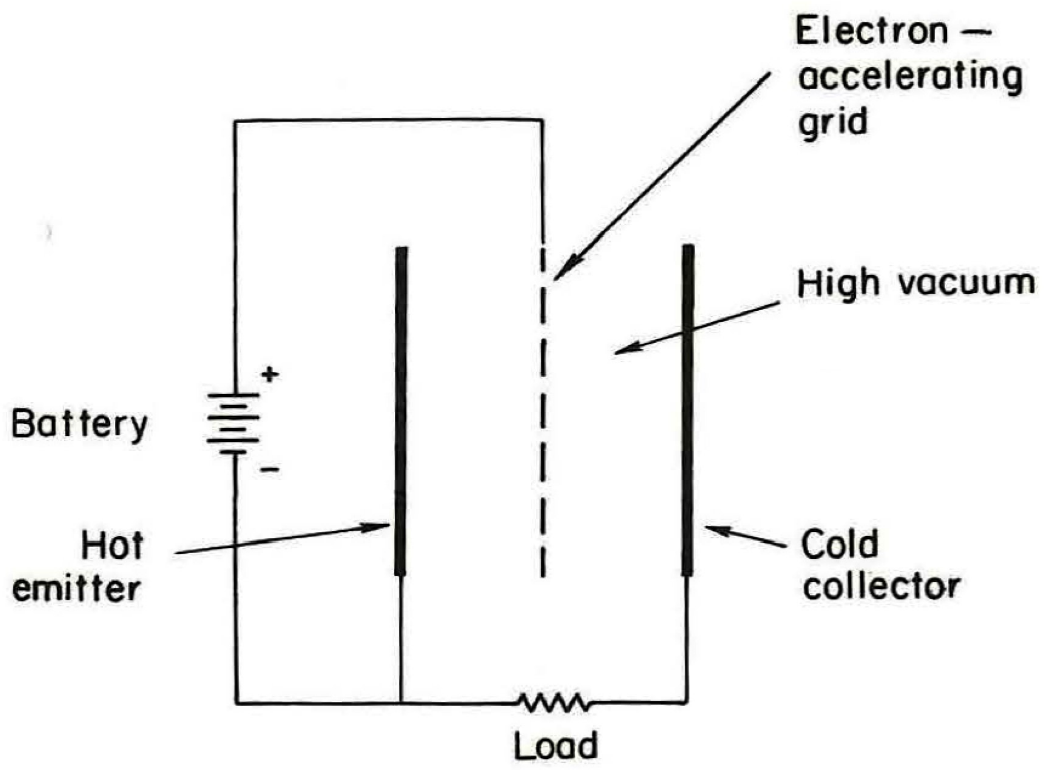
   large-scale feasibility not obvious (yet)

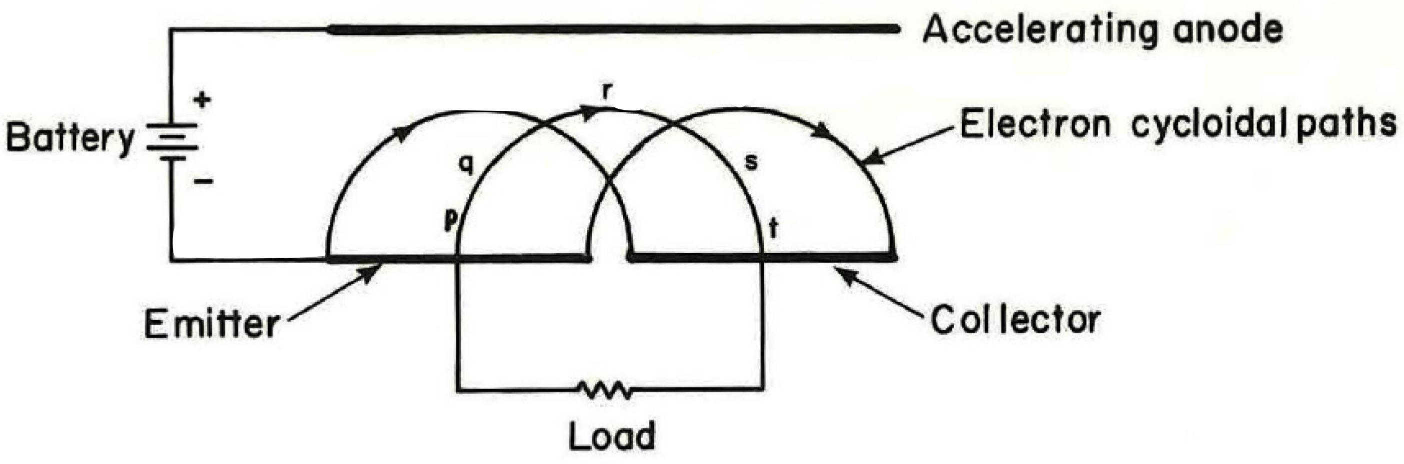
3) **Grid** to accelerate electrons out of the cloud

   not working

   (see, *e.g.,* G.N. Hatsopoulos *et al.*, Thermionic Energy Conversion, Vol. 1 (1973))

Accelerating Electrodes



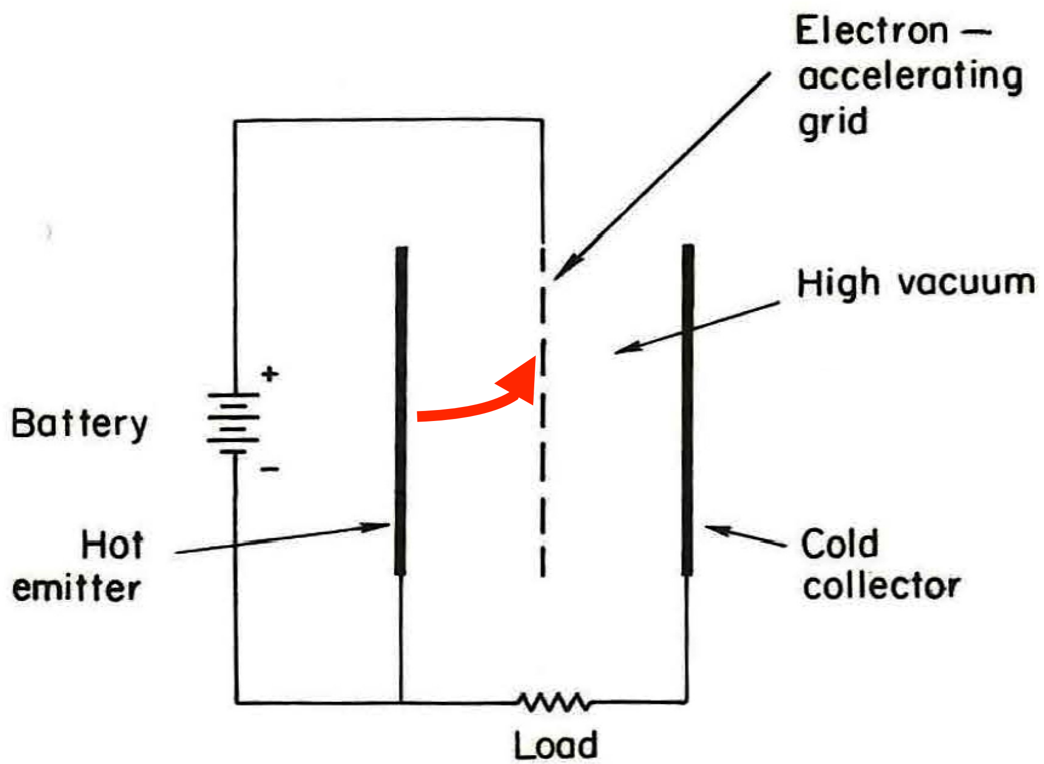


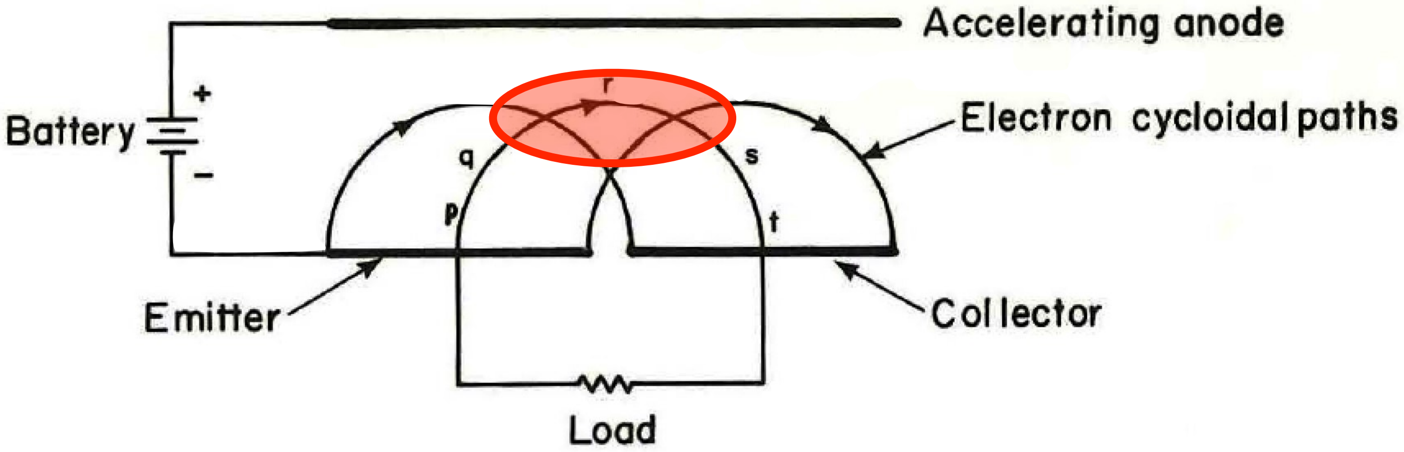
large I_G, small I_{EC}:

'… not practical at present', '… magnetic triode even more impractical than magnetic diode'

G.N. Hatsopoulos *et al.*, Thermionic Energy Conversion, Vol. 1 (1973)

Accelerating Electrodes





- electrons accelerated into the grid

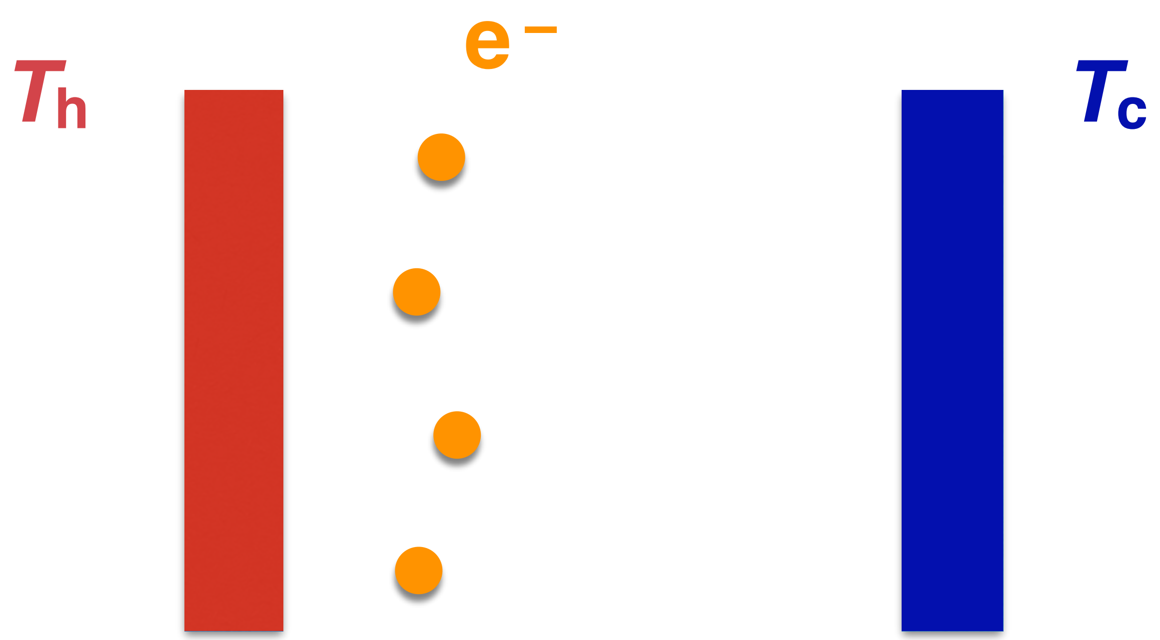
- enhancement of space charge
- E-C distances intrinsically too large

large I_G, small I_{EC}:

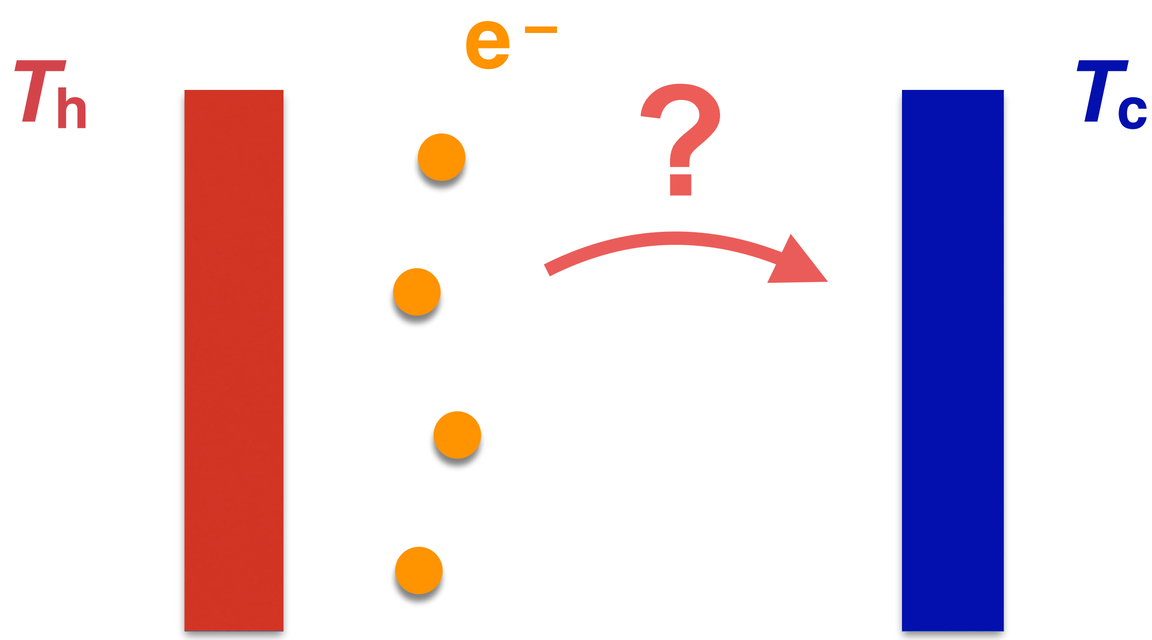
'… not practical at present', '… magnetic triode even more impractical than magnetic diode'

G.N. Hatsopoulos *et al.*, Thermionic Energy Conversion, Vol. 1 (1973)

Thermoelectronic Power Conversion

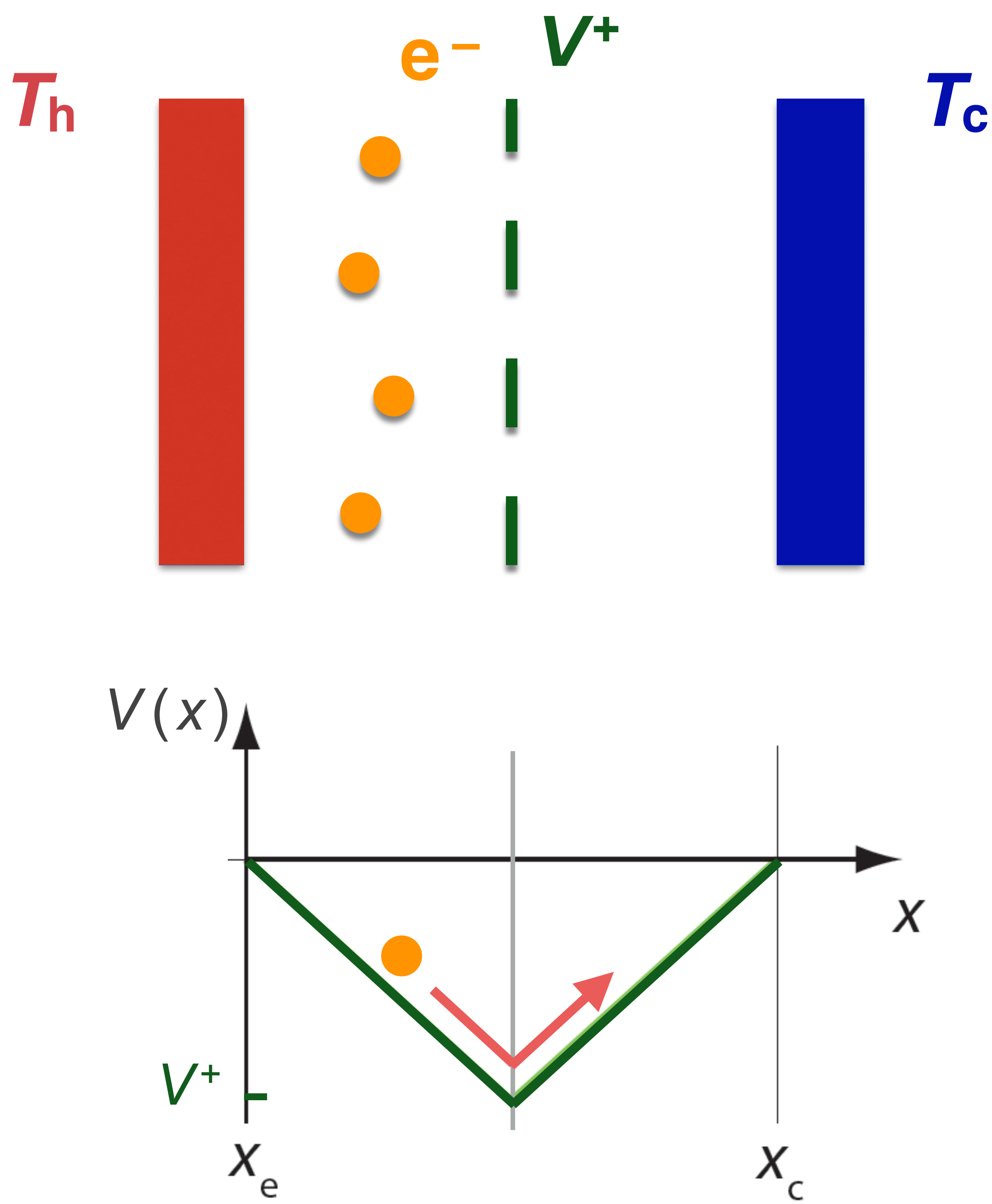


Thermoelectronic Power Conversion



How to transfer the electrons without energy expenditure?

Thermoelectronic Power Conversion



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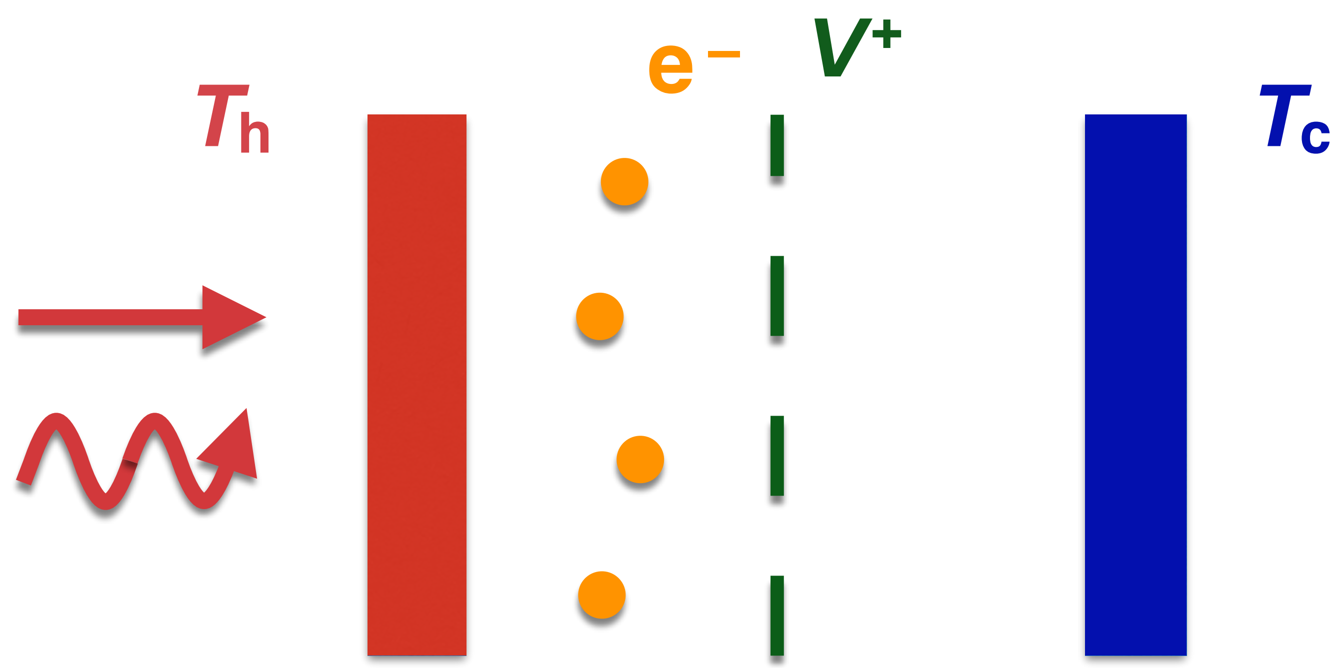
Thermoelectronic Power Conversion

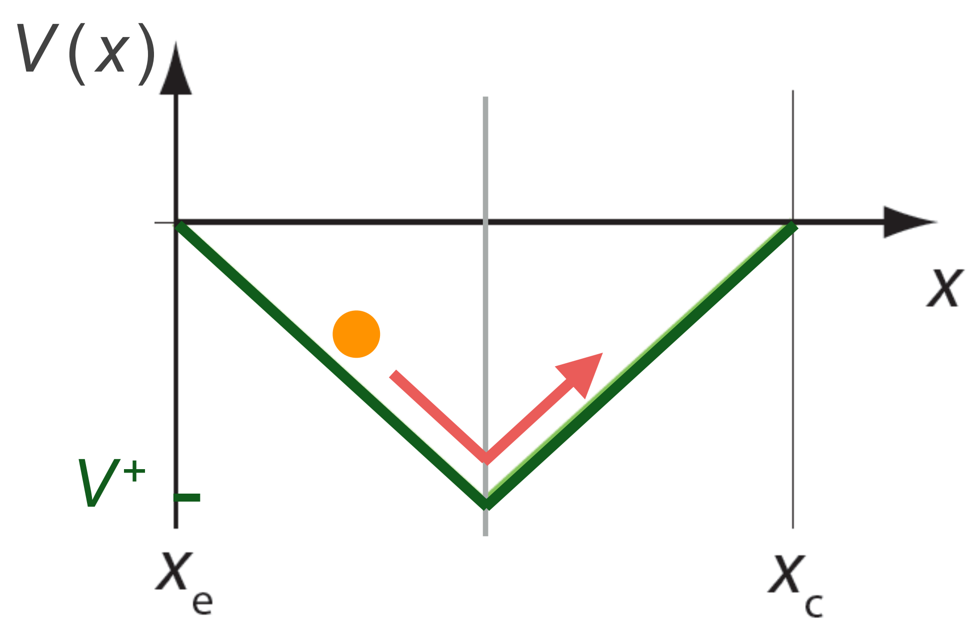
PETE

photoeffect

tunneling-enhanced

thermionic emission





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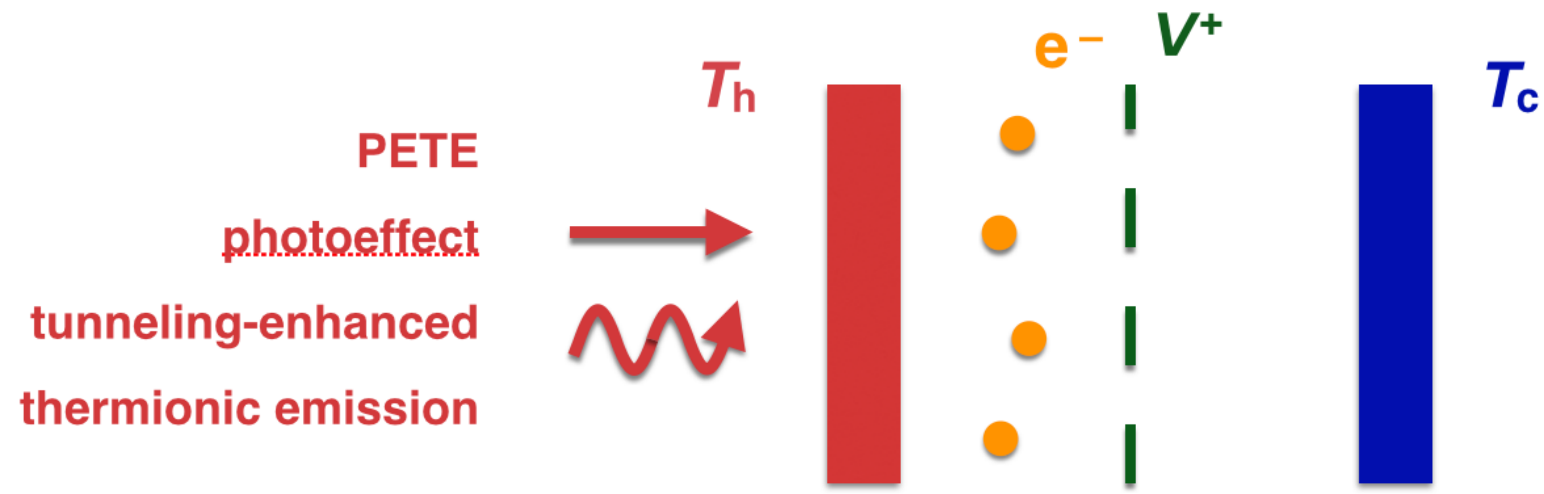
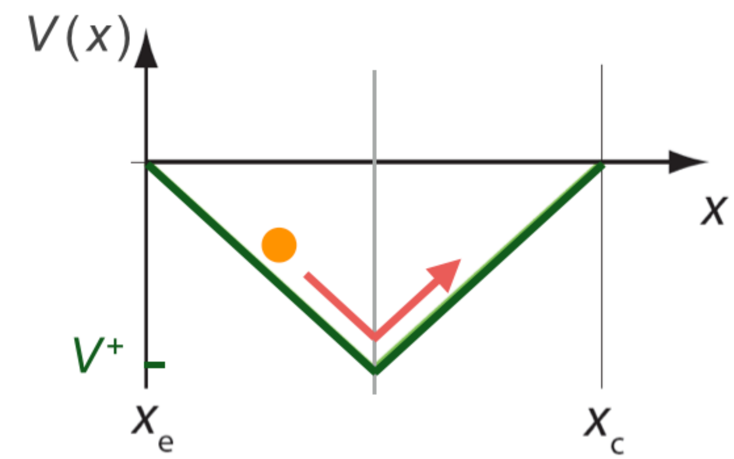
Thermoelectronic Power Conversion

- **any emission process**
  also non-thermionic
- **no ions**, no “thermions”
- the **electrons** essential

⟶ **“thermoelectronic”**





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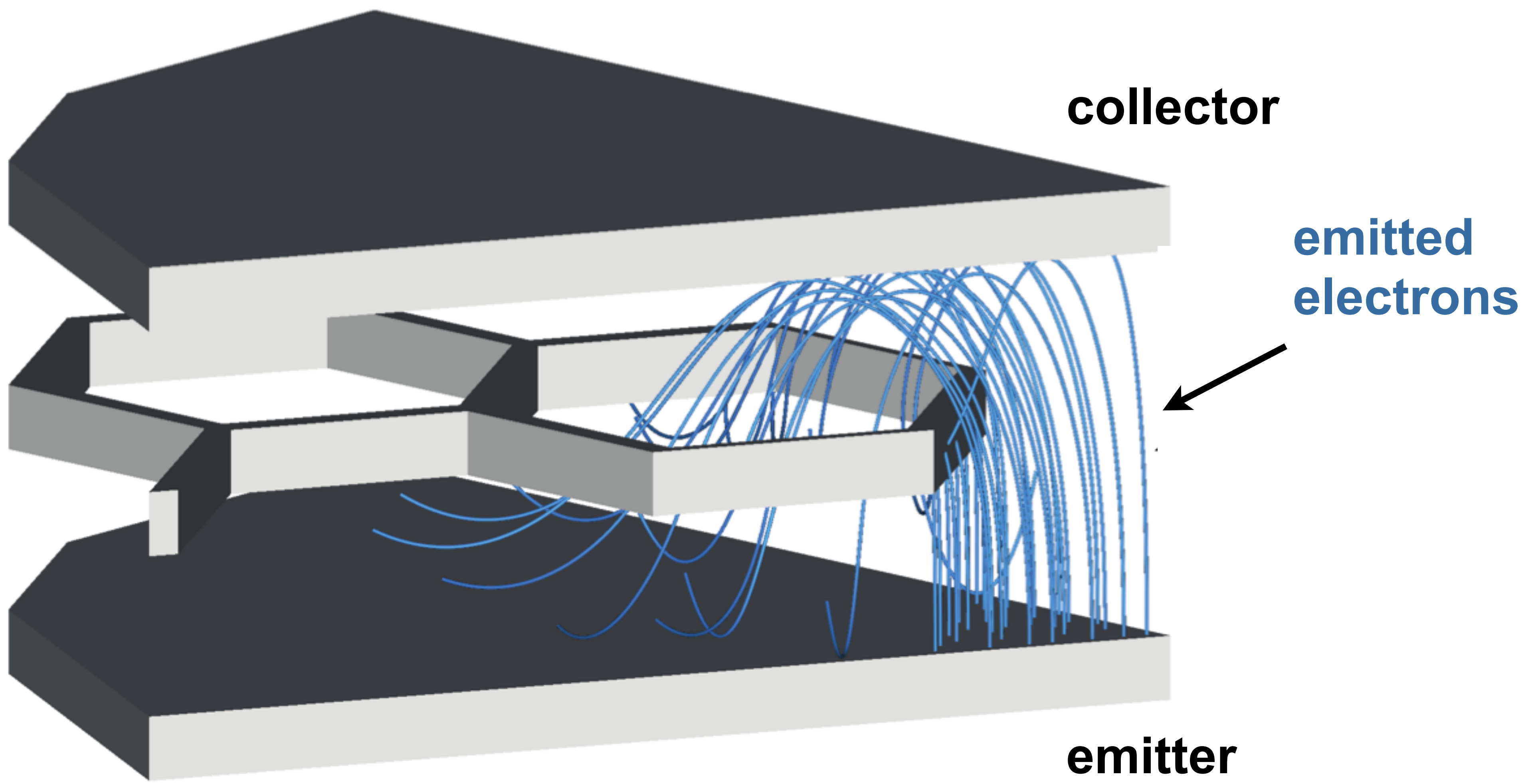
3D Model Calculations

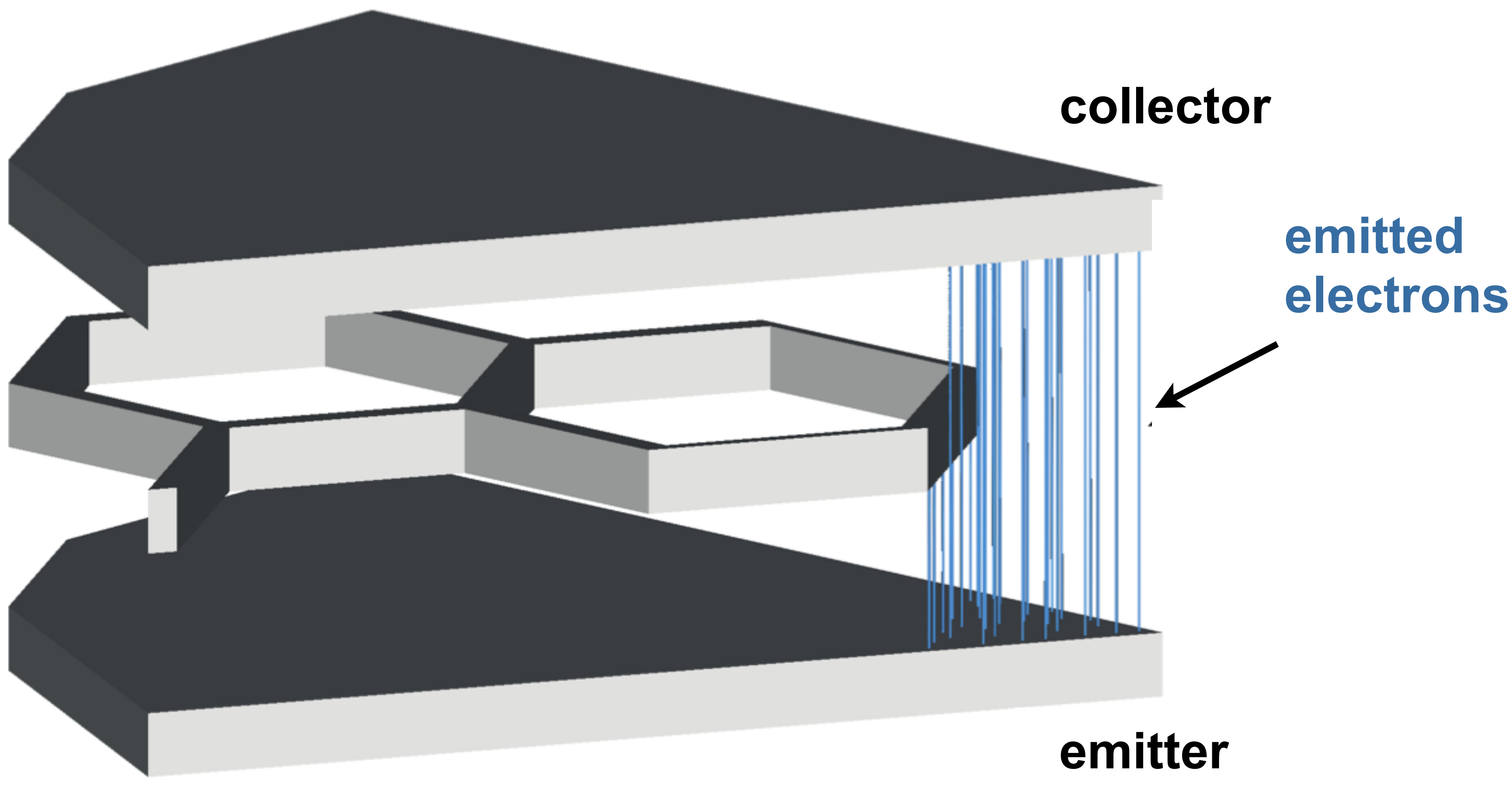
$B = 0$ T, $V_g = 10$ V, $d_{ec} = 100$ µm



´*Coulomb*´, Integrated Engineering Software

3D Model Calculations

$B = 1$ T, $V_g = 10$ V, $d_{ec} = 100$ µm



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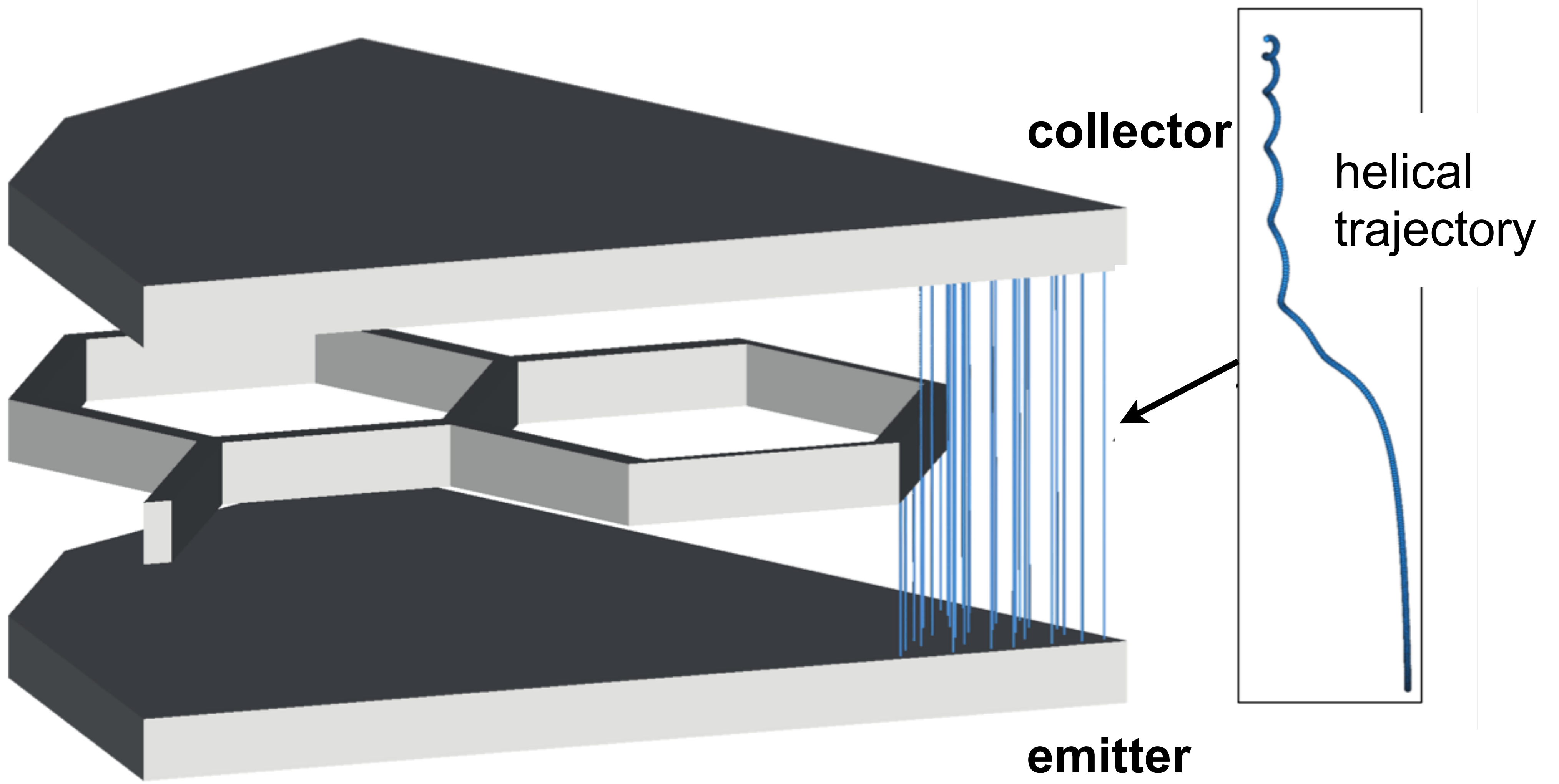

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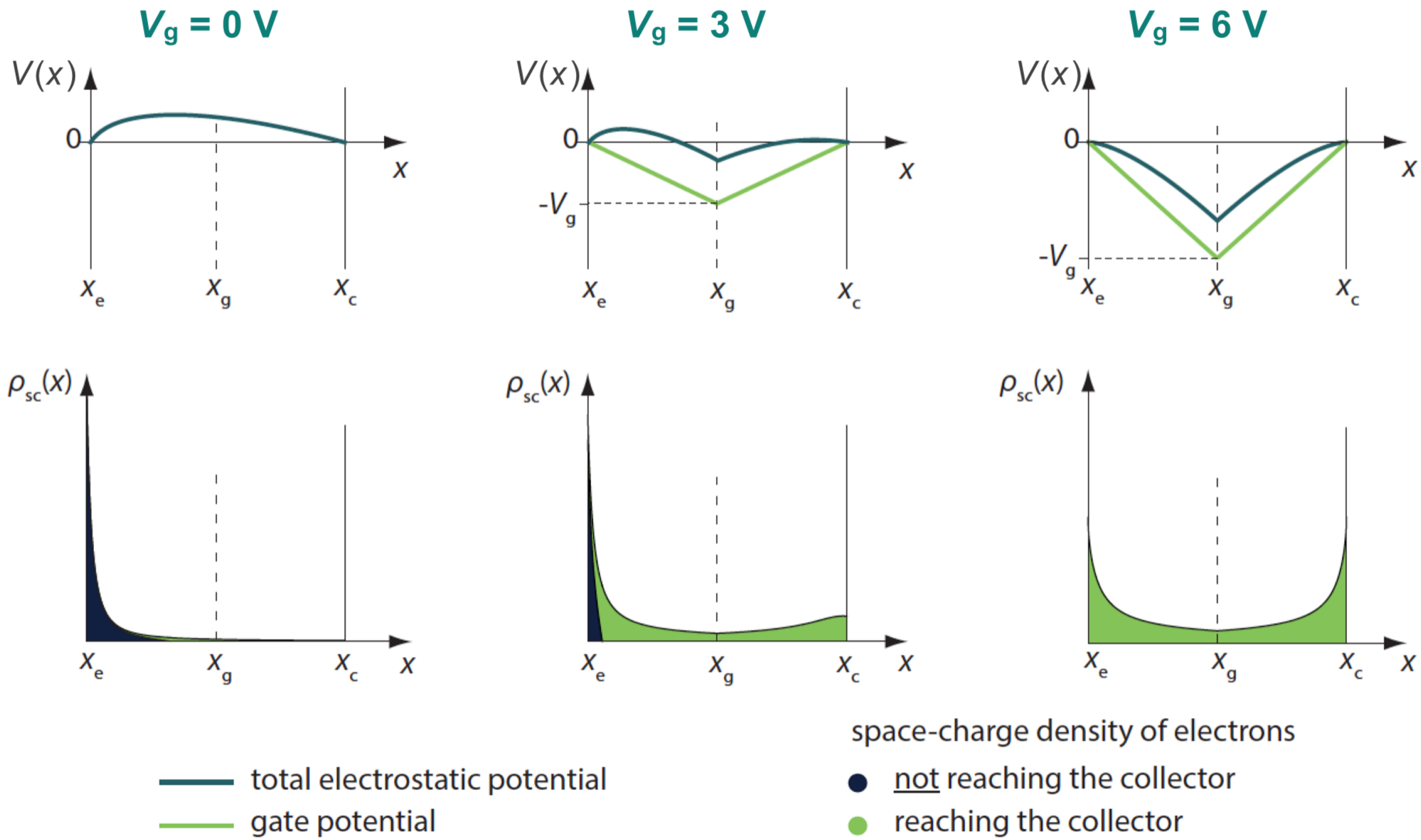
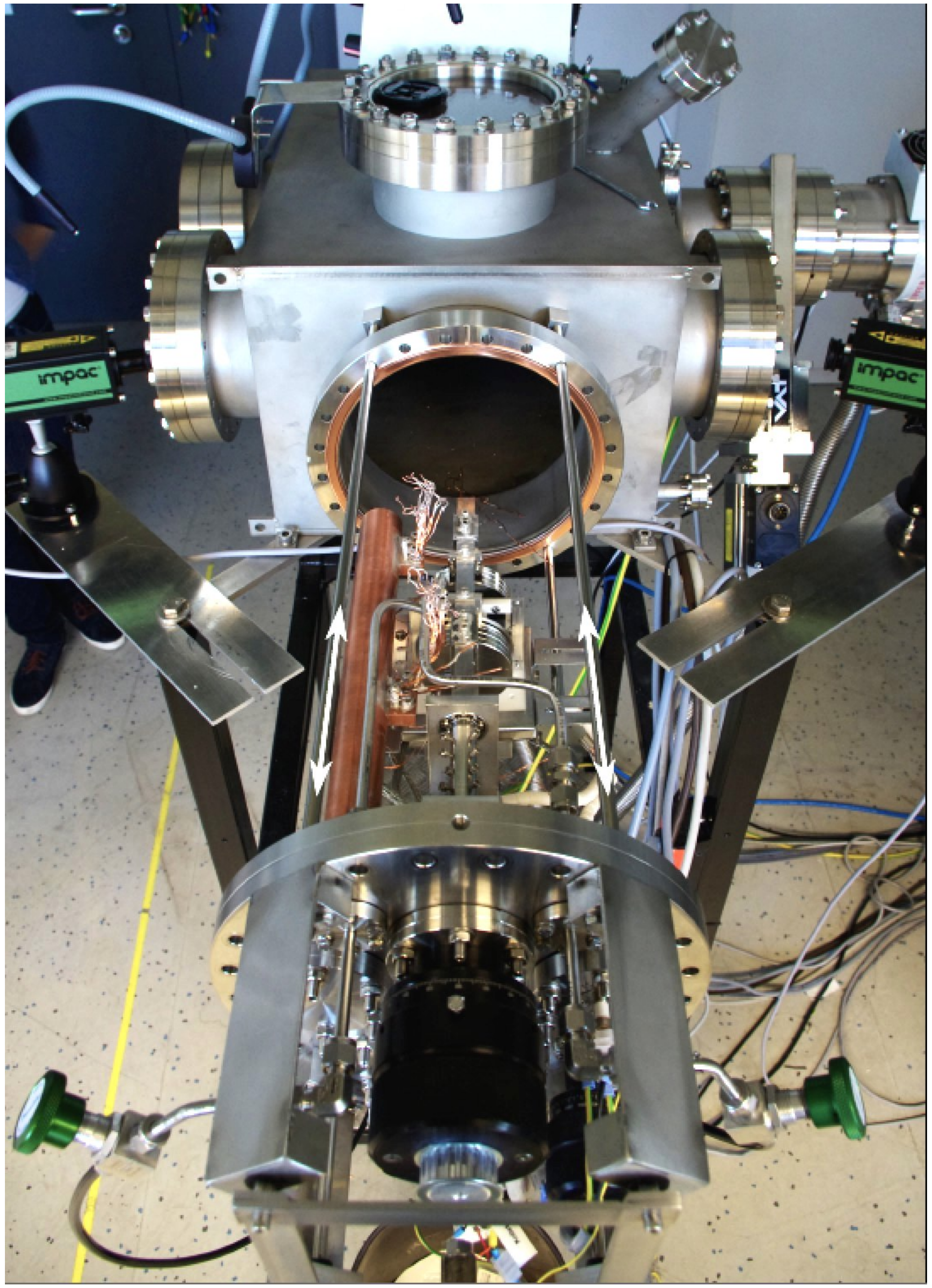
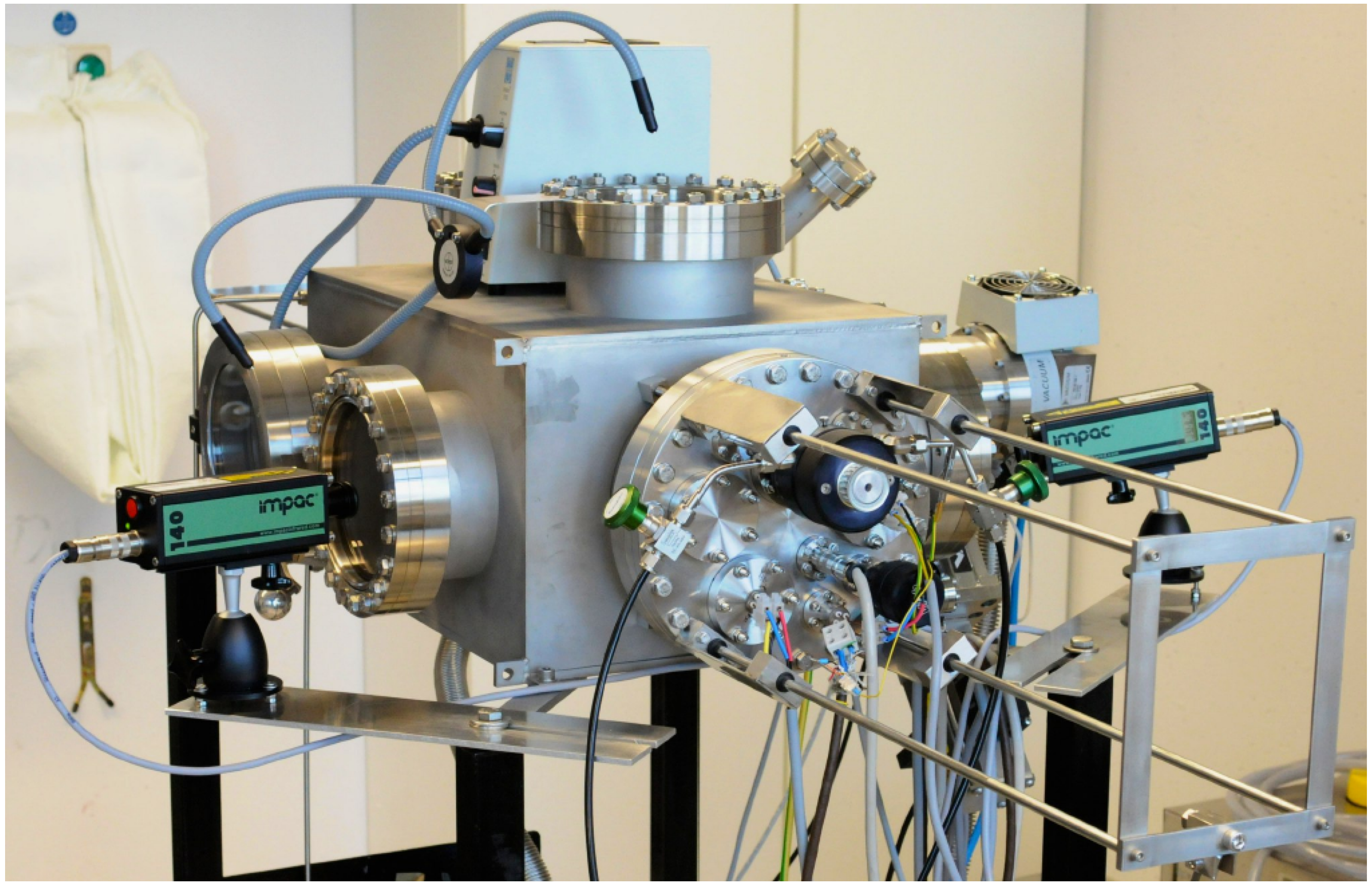
Model Calculations



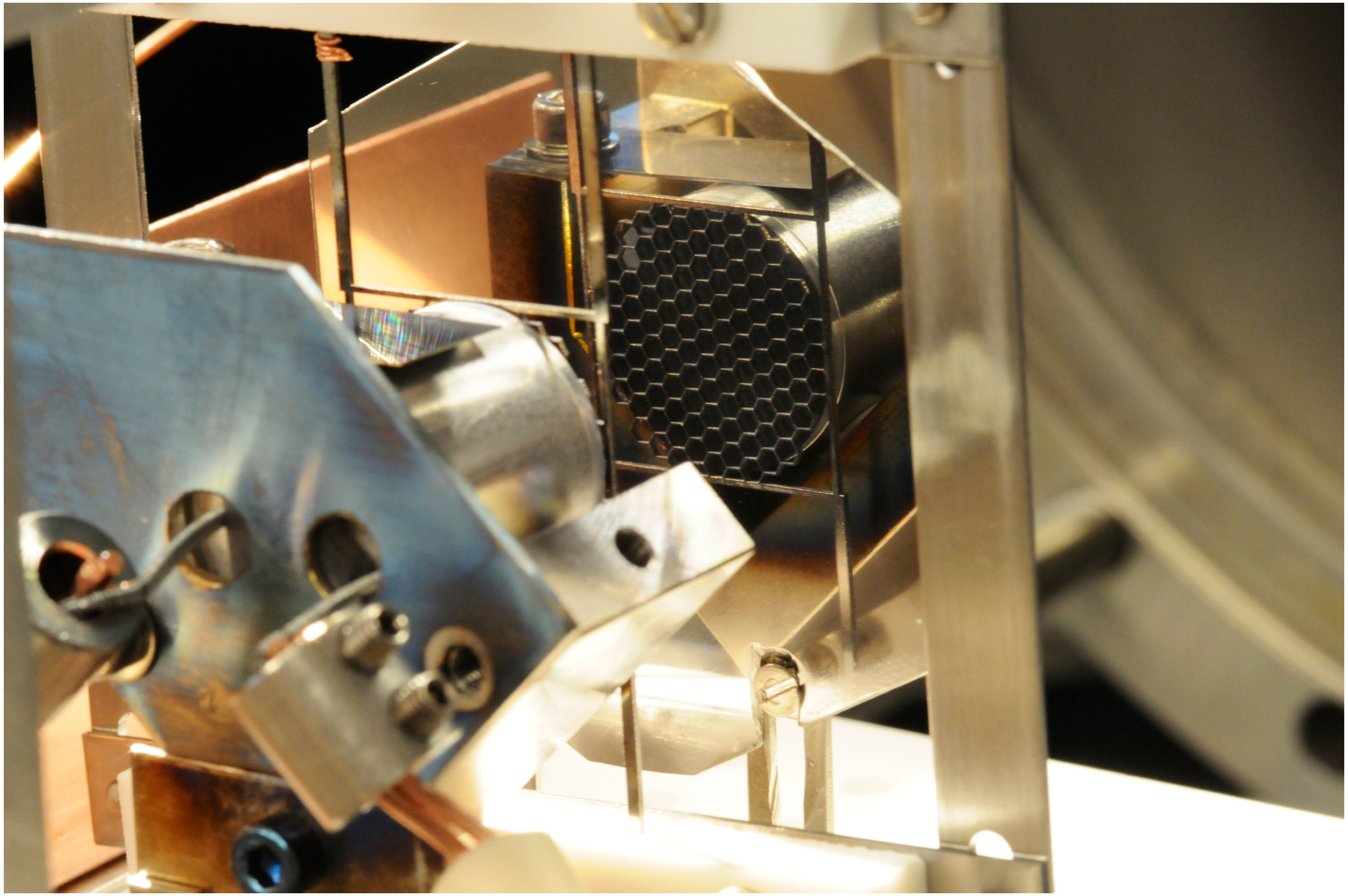
- **annihilation of space charge due to electric field superposition and enhanced electron velocities**

Thermoelectronic Generator

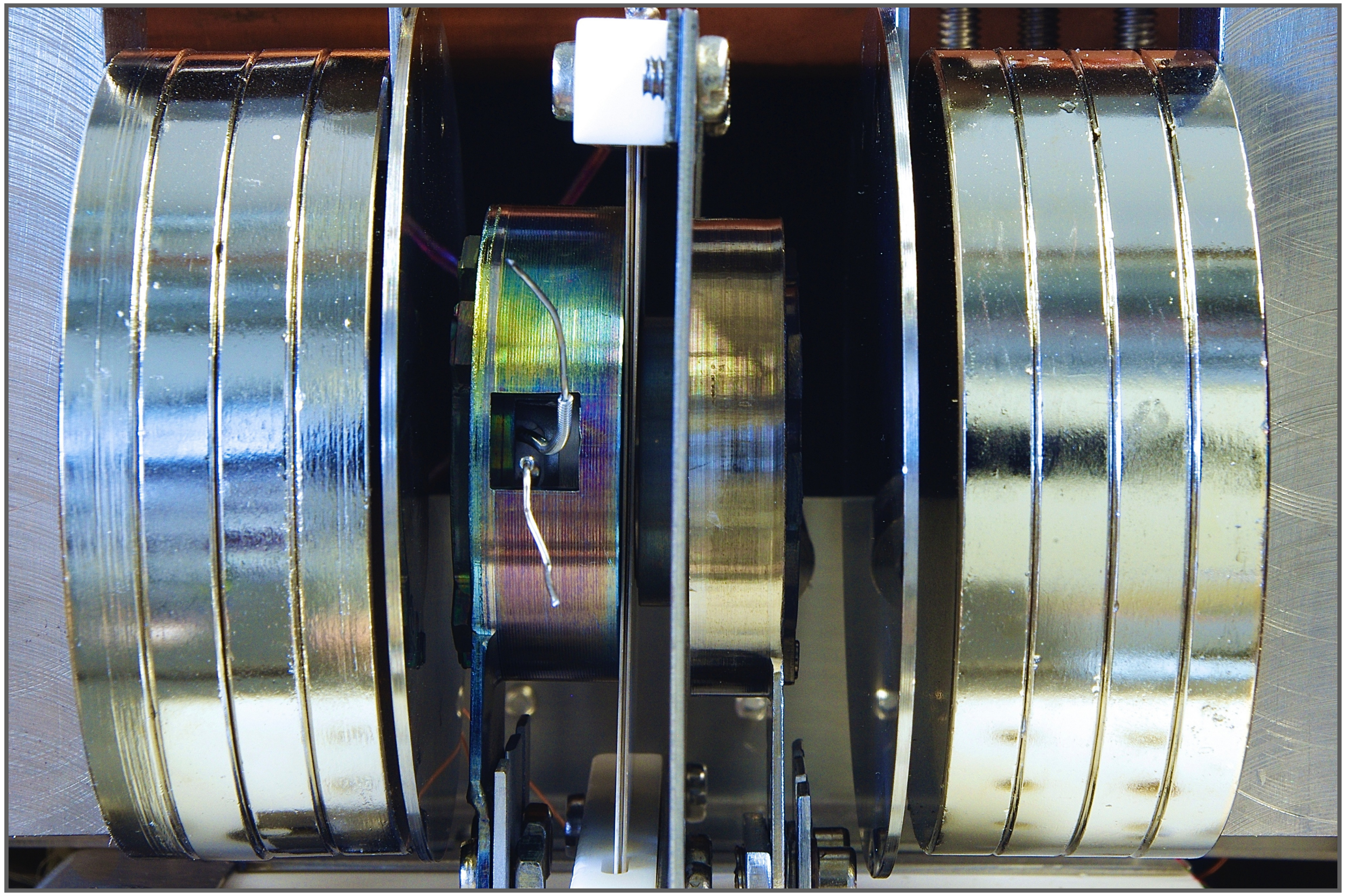




Thermoelectronic Generator

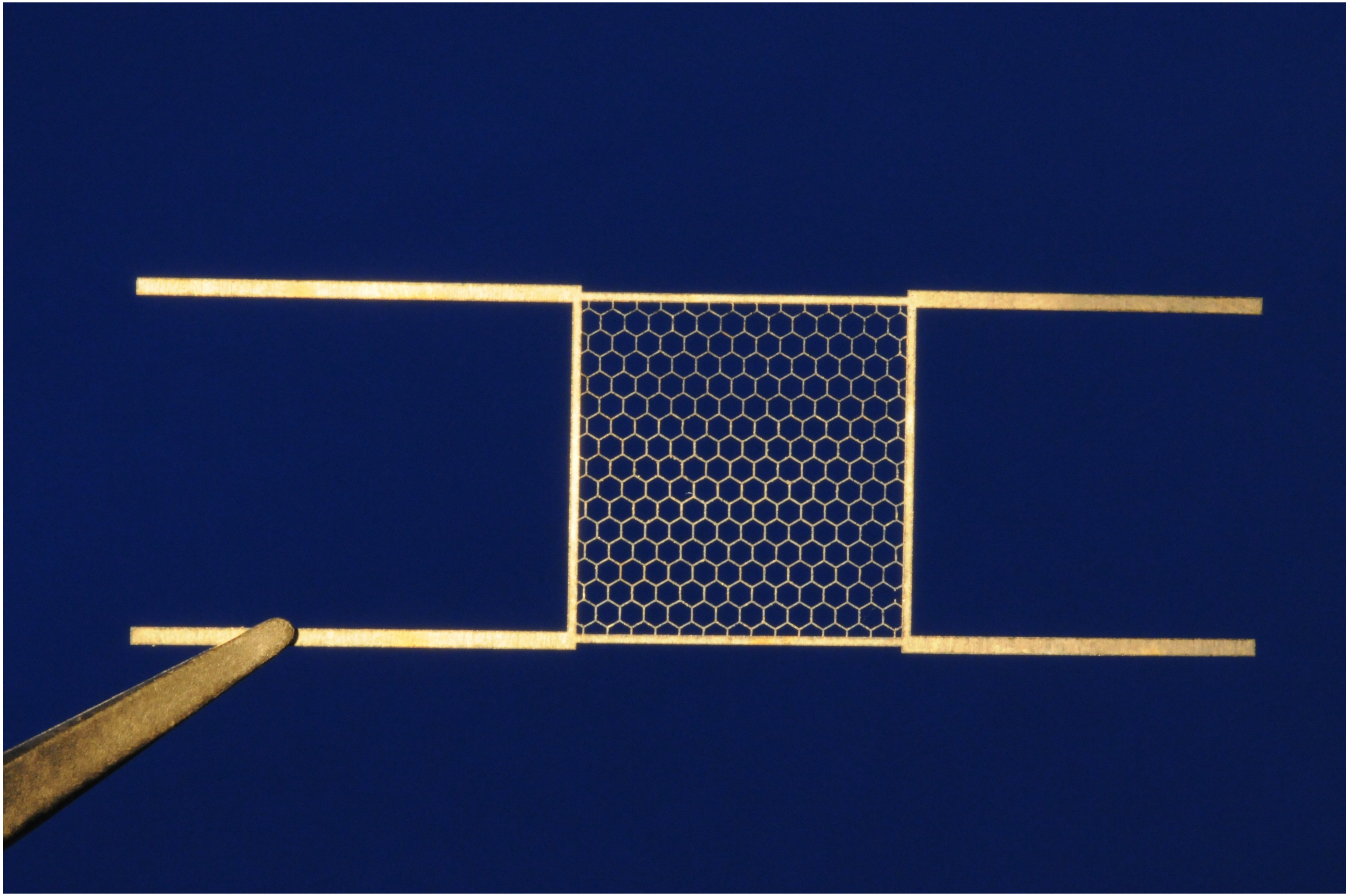


Thermoelectronic Generator

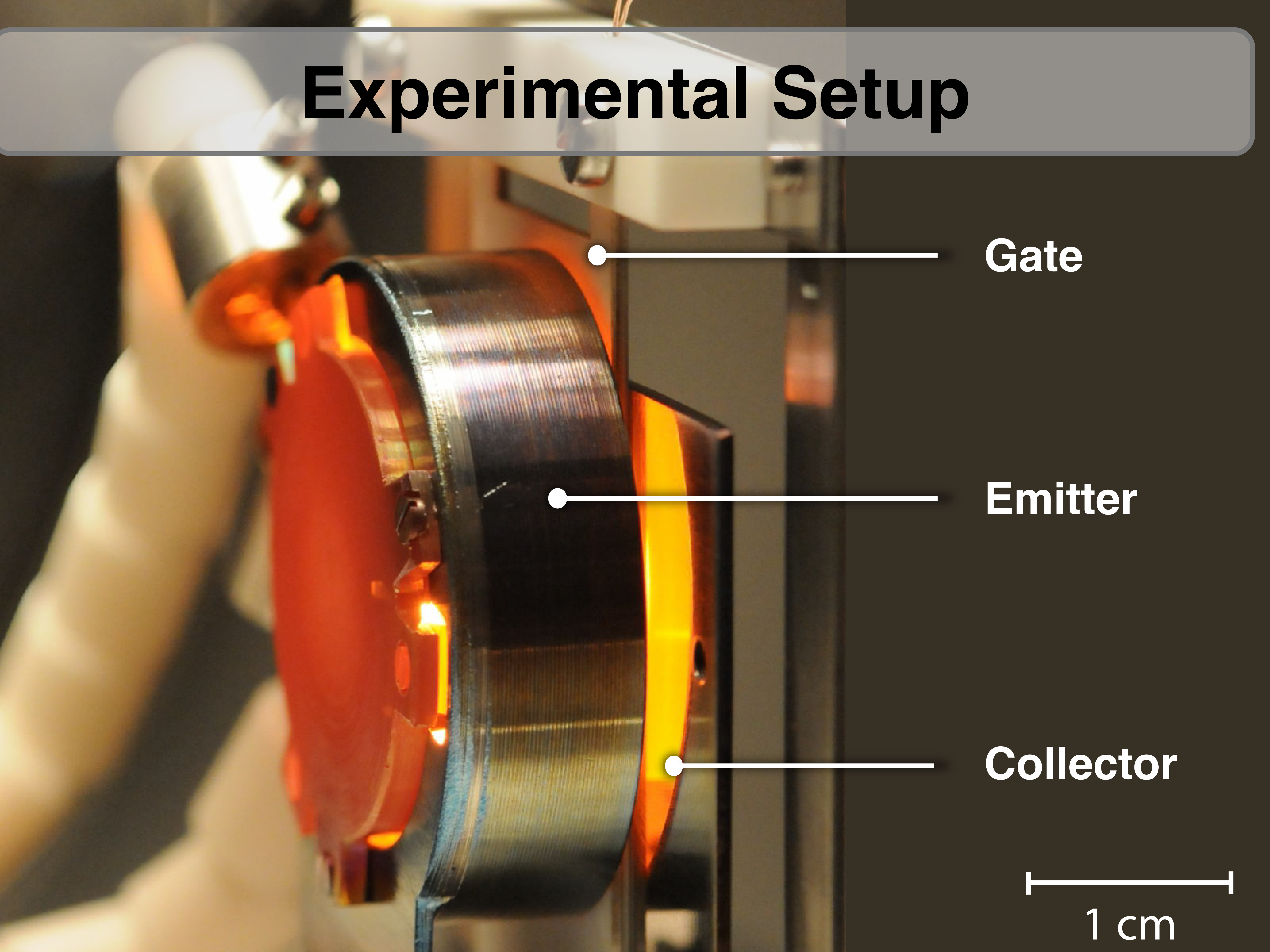


6 cm

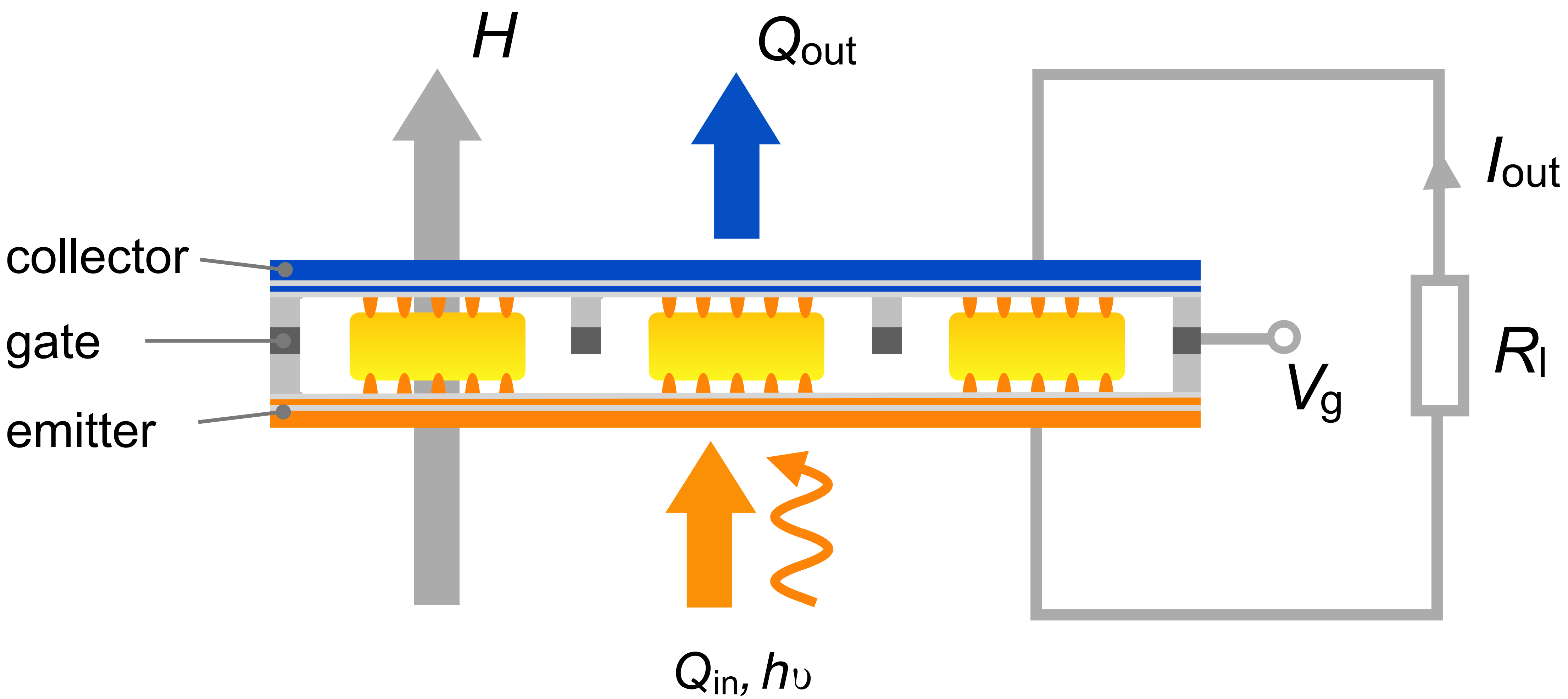
W-Grid



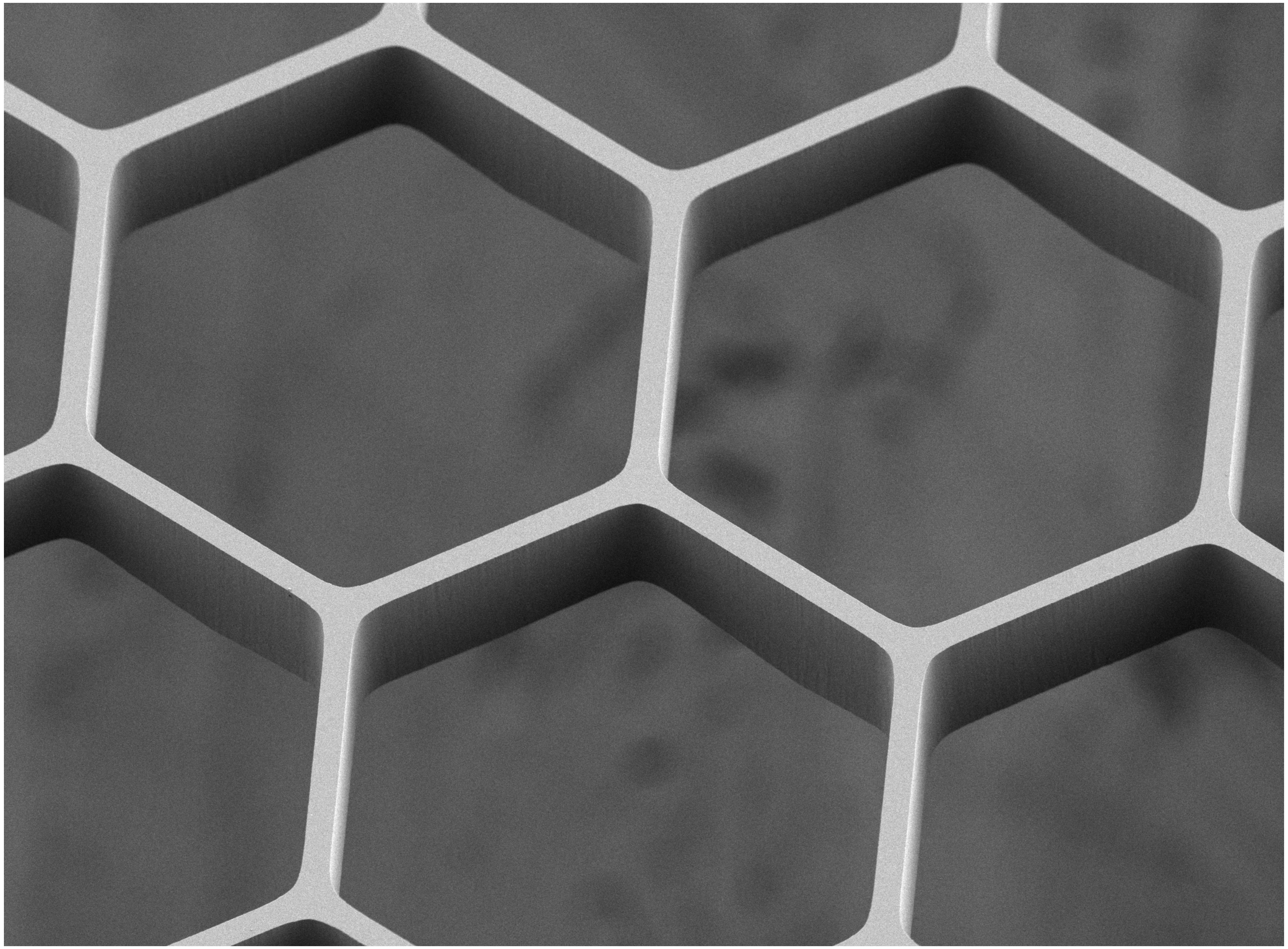
Experimental Setup



Flip-Chip Generators

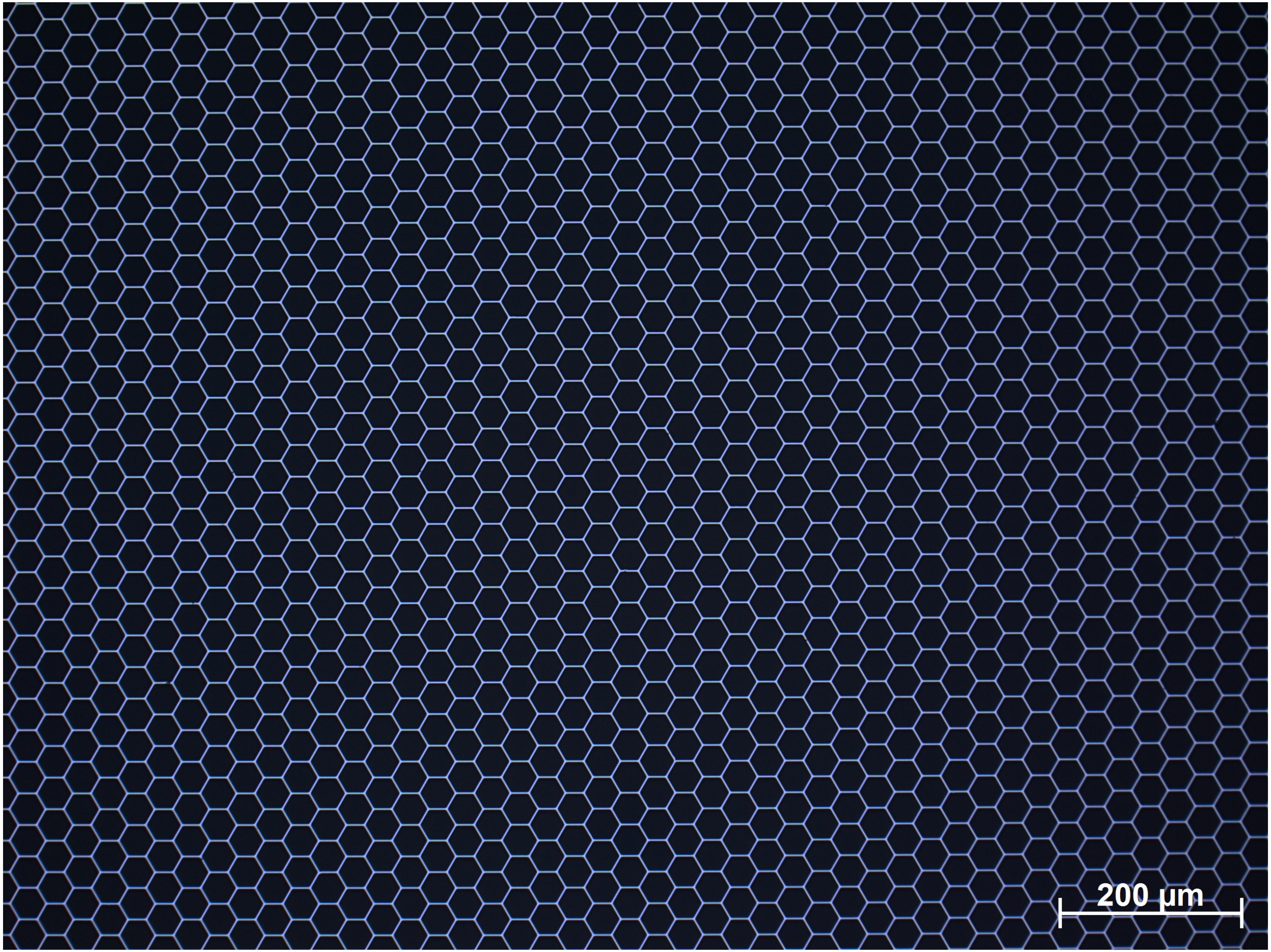


Si-Grid

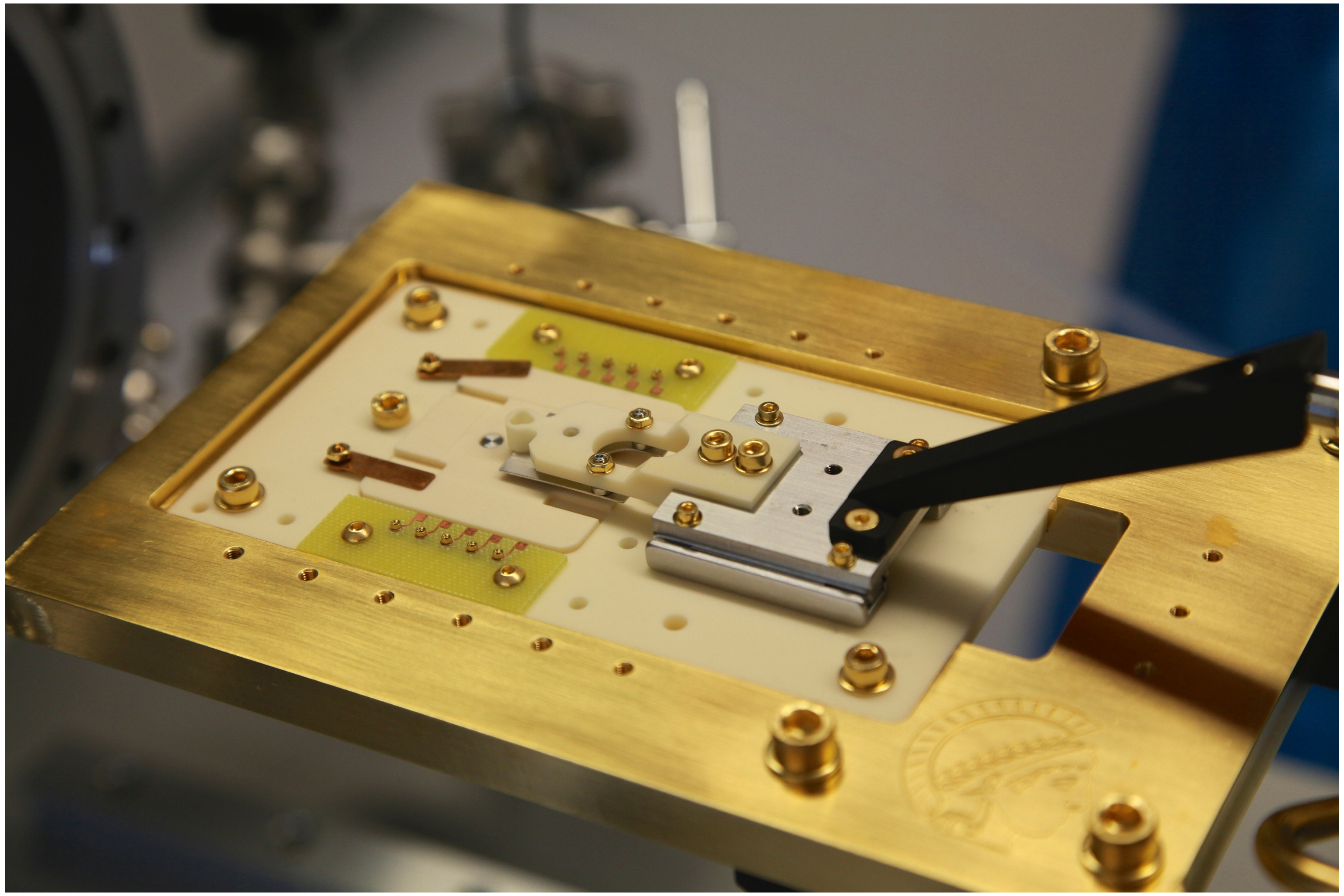


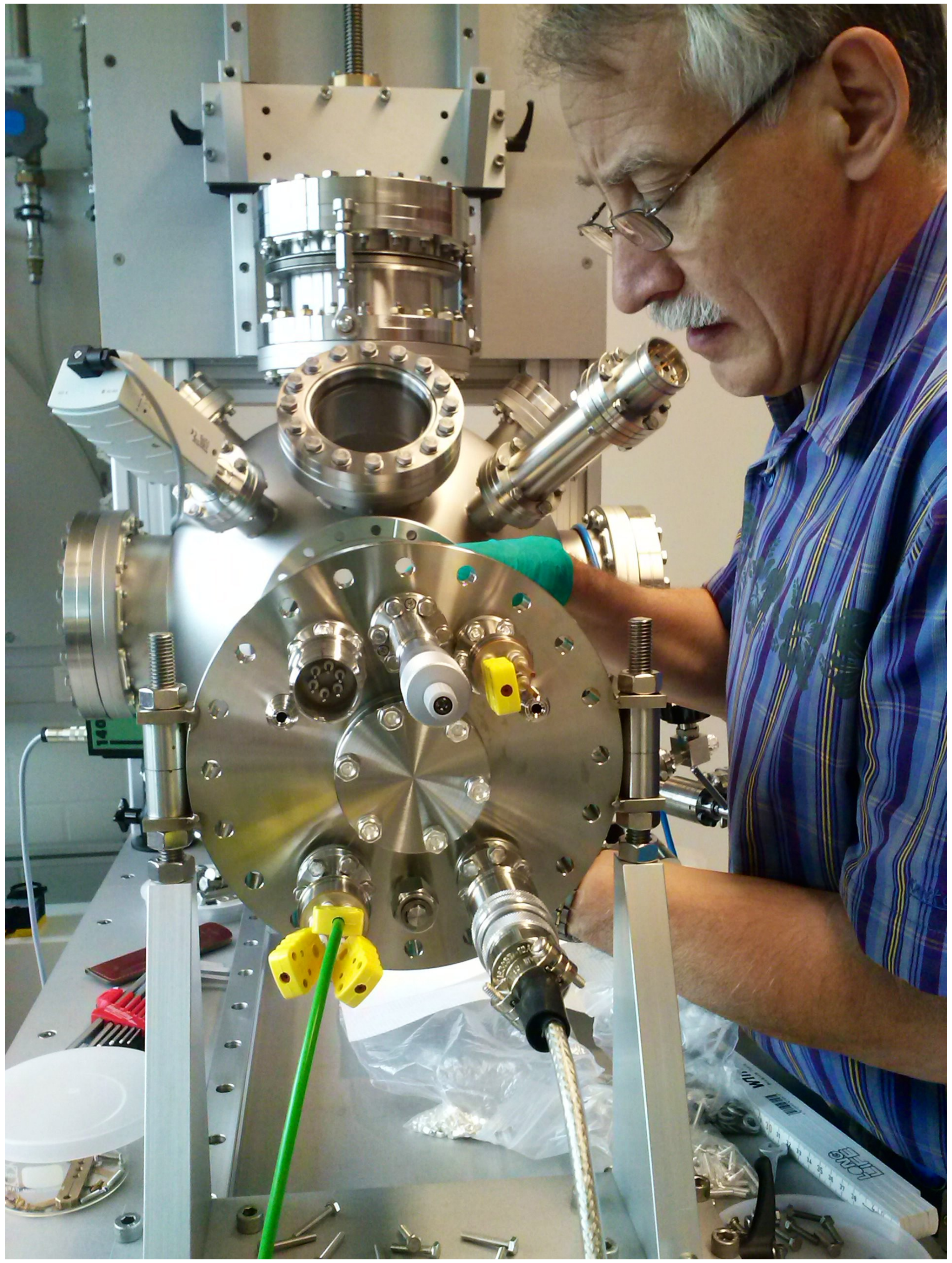
10 µm

Si-Grid

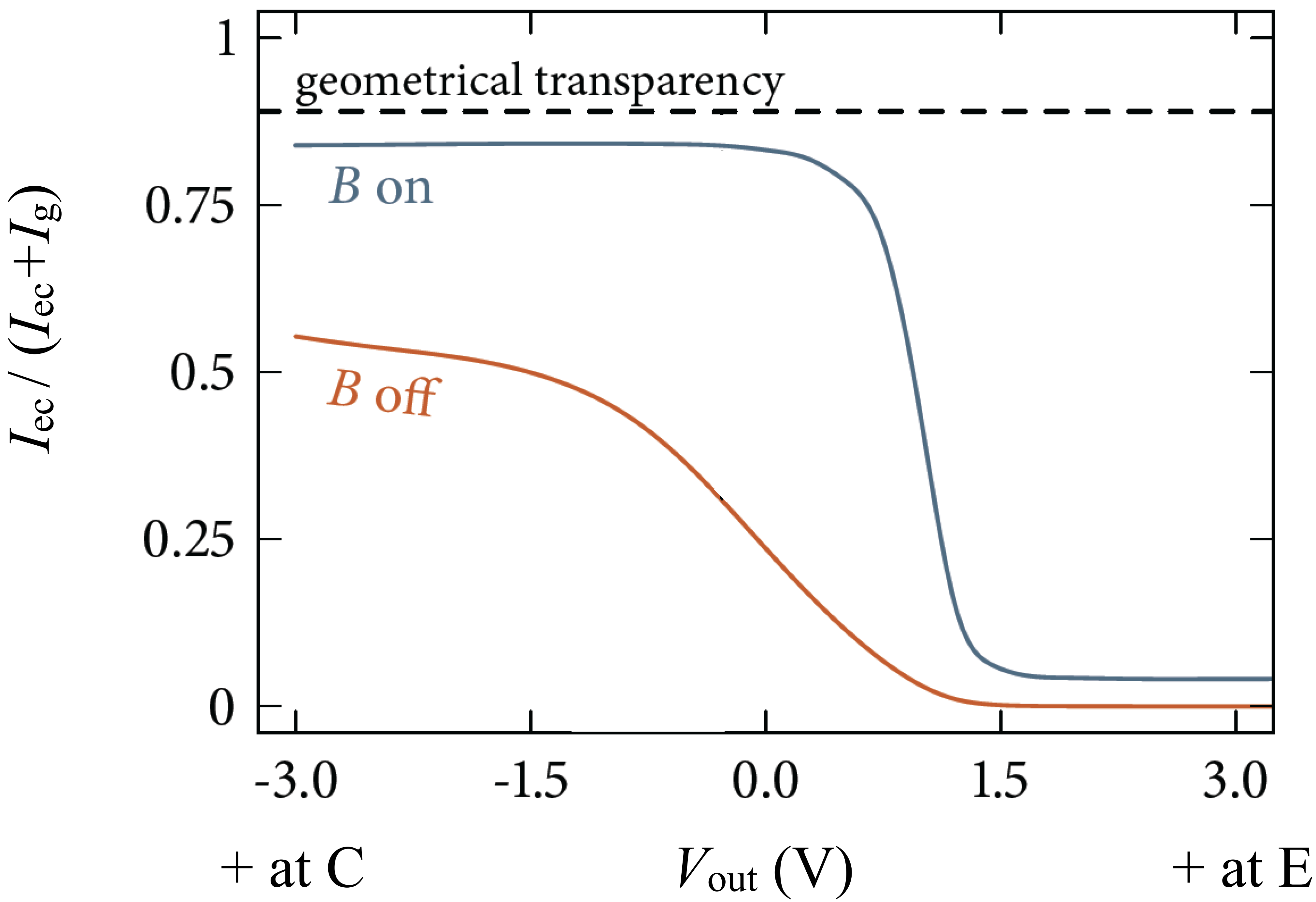


Flexible Experimental Base - October 2014



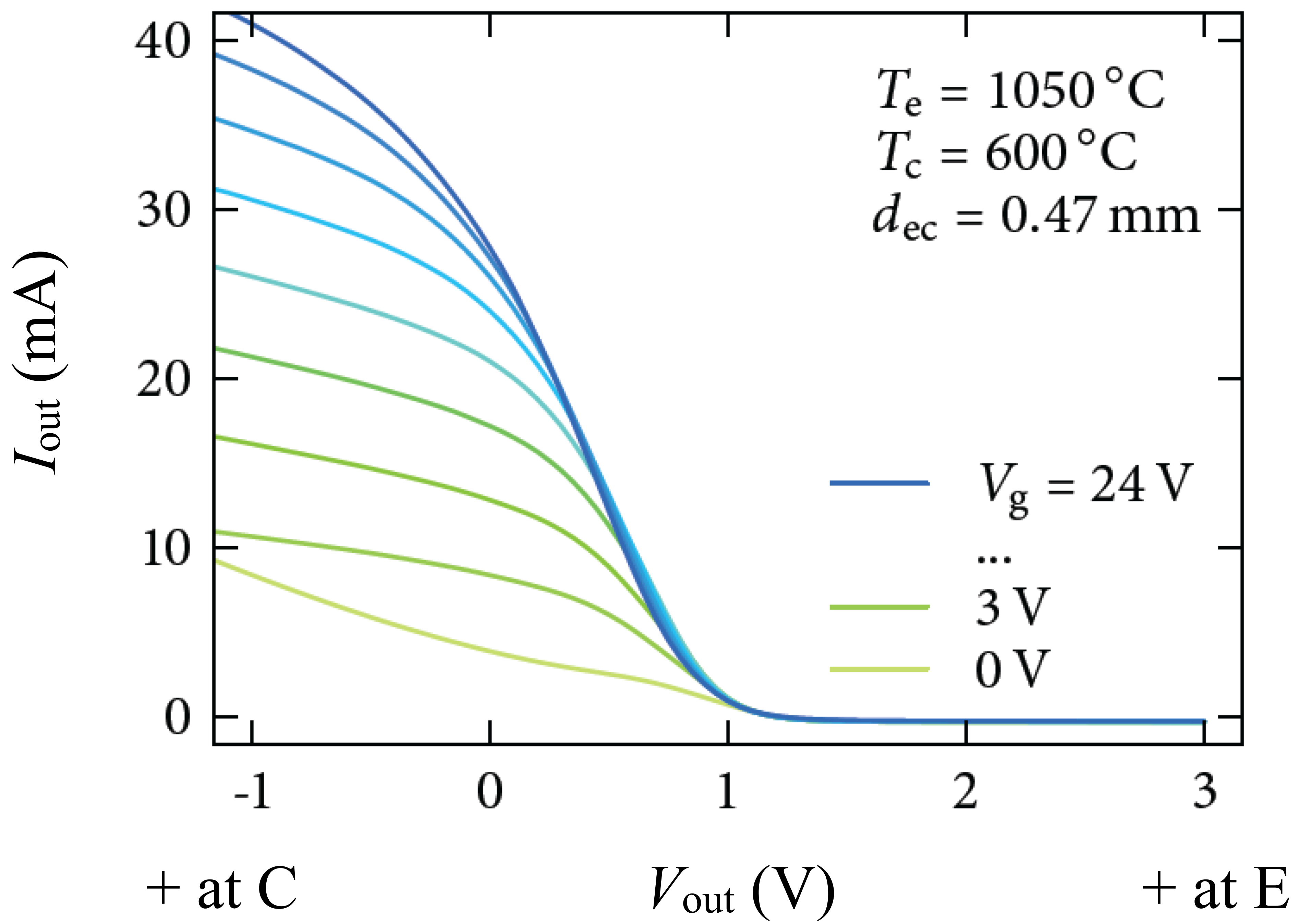


Measured Output Current Densities

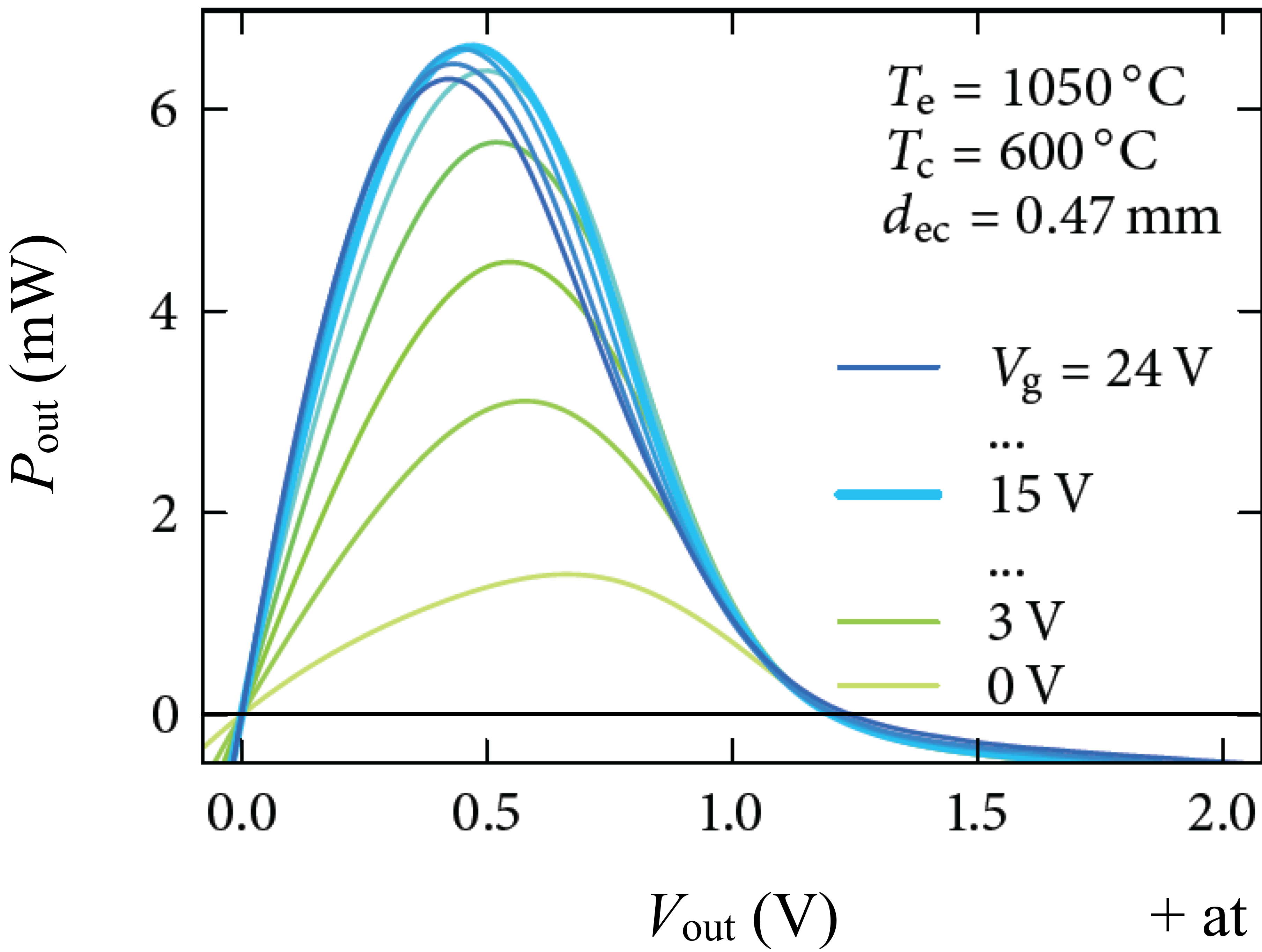


$V_g = + 6$ V
$T_e = 1100$ C
$d_{ec} = 1$ mm
$w = 1.6$ mm

Measured Collector Currents

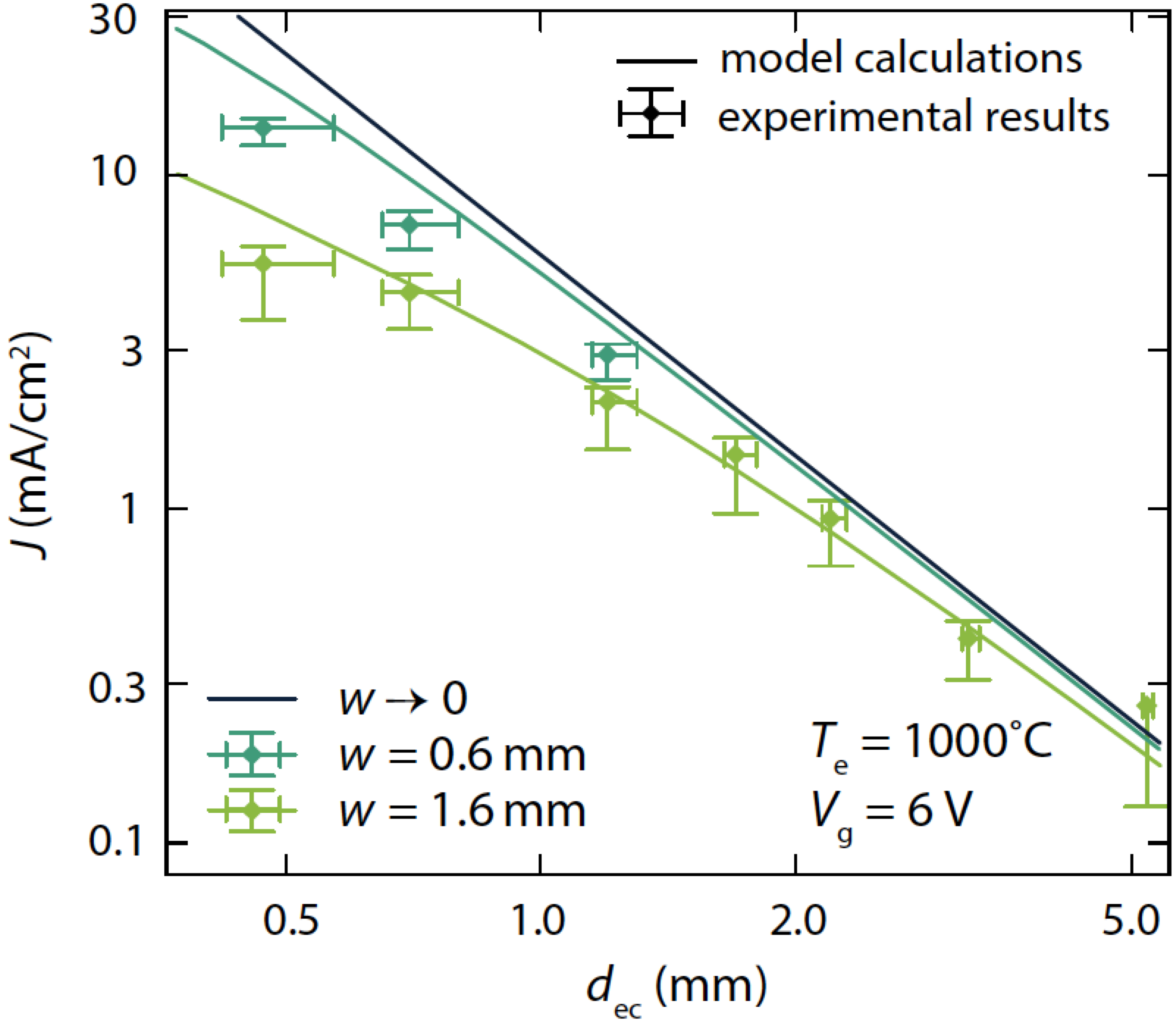


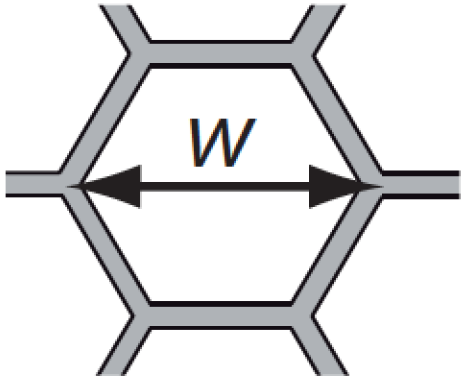
Measured Output Power



+ at E

Output Current Densities





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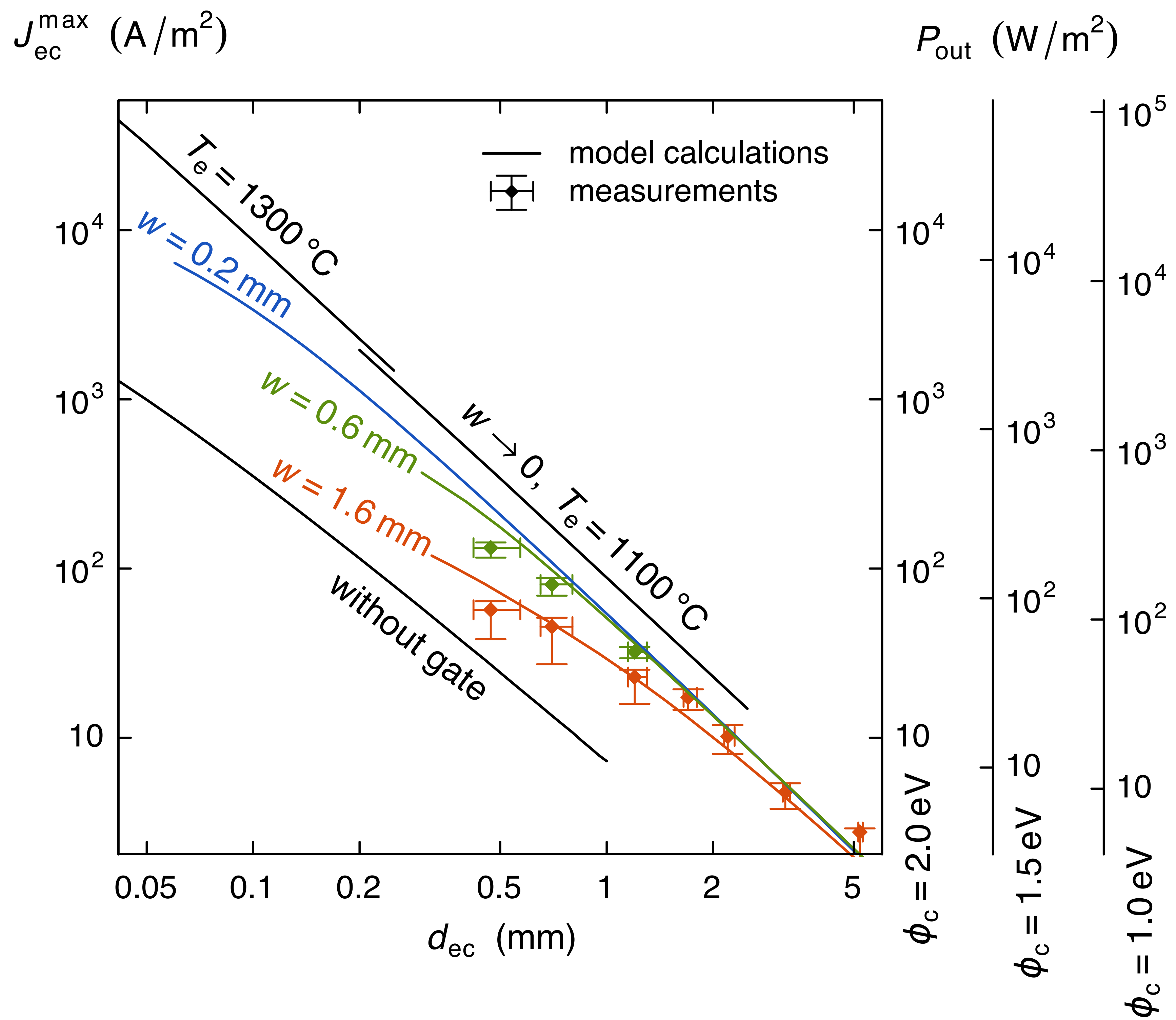
Projected Power Densities



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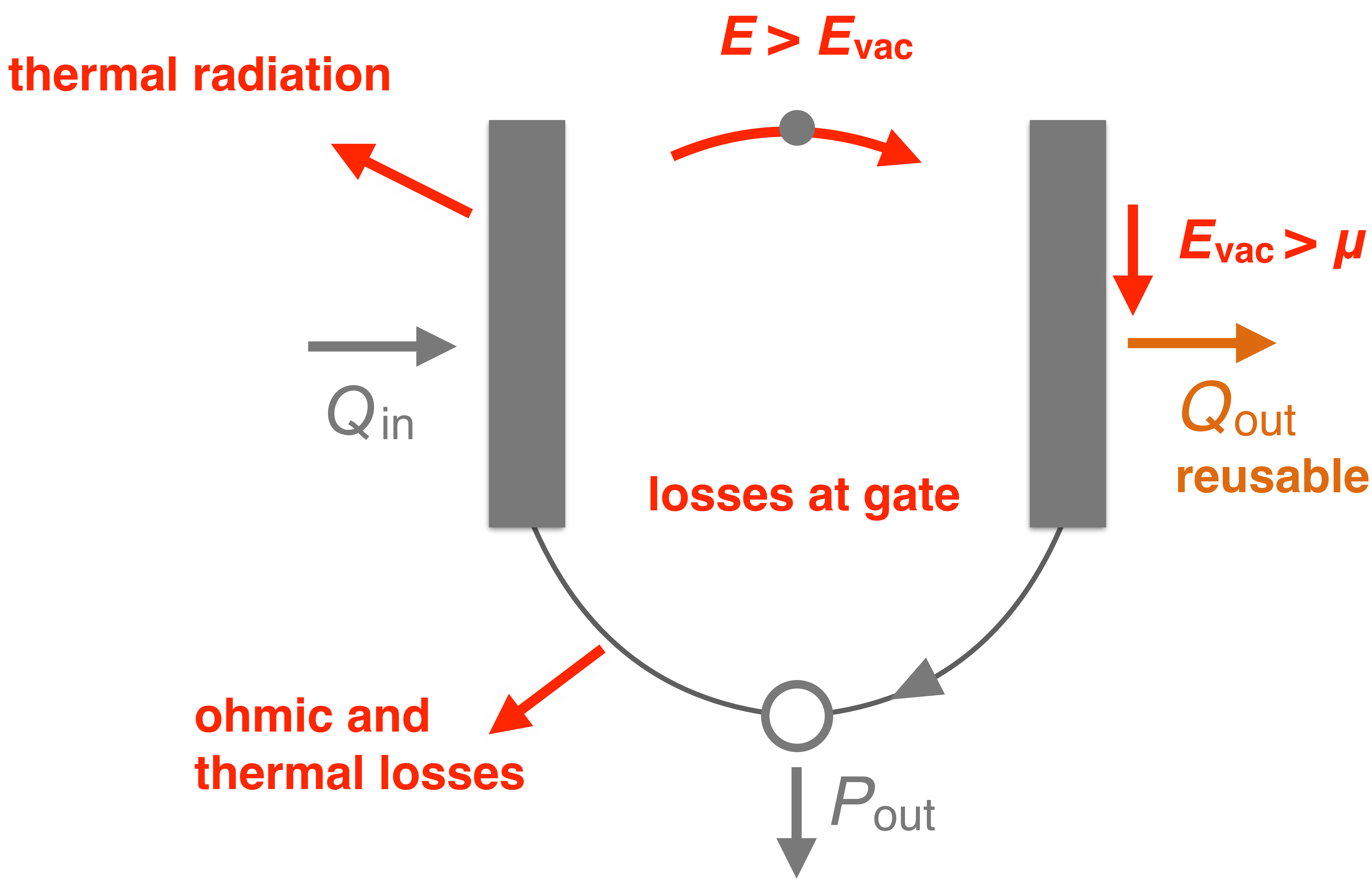
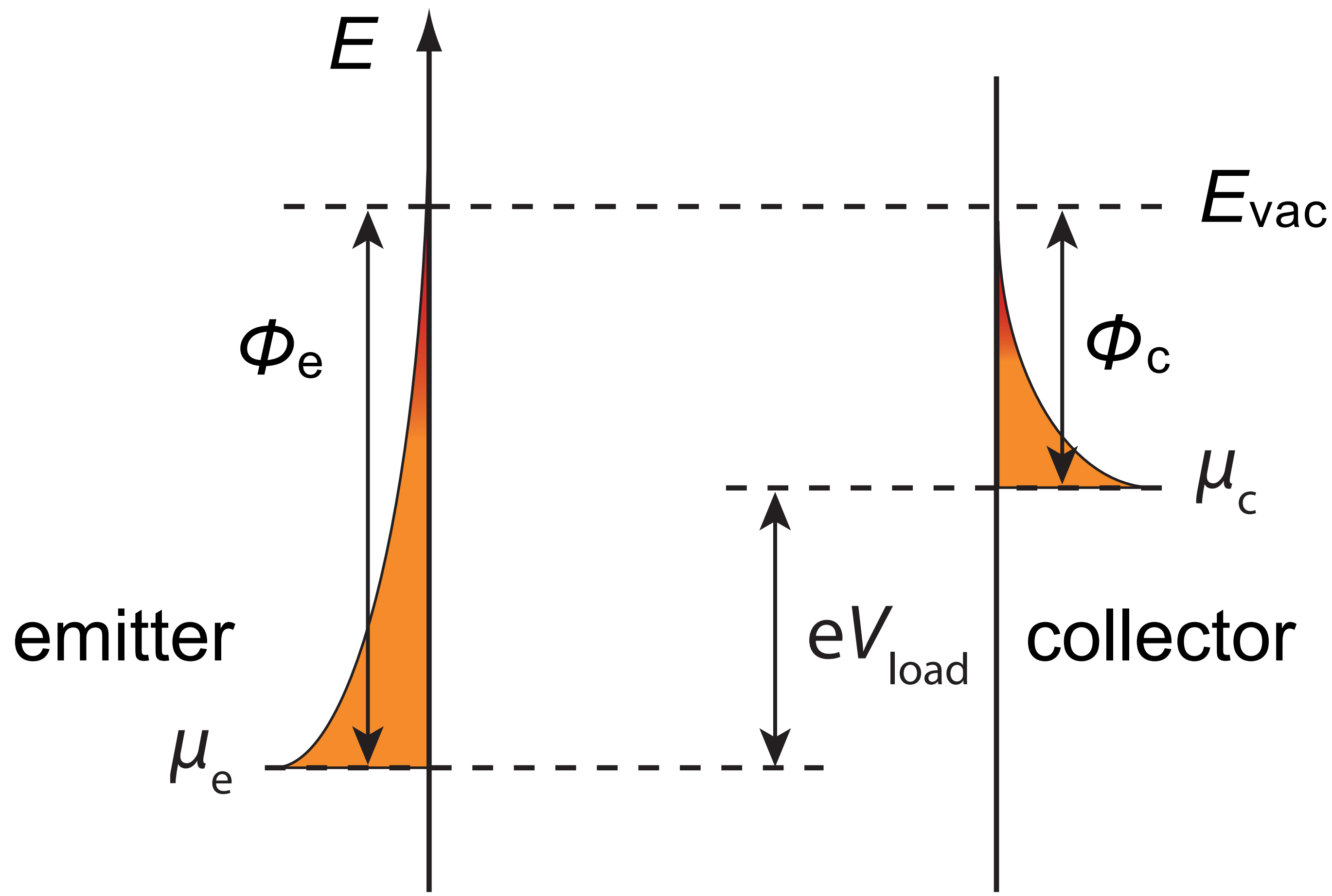
Fundamental Loss Channels



The Ultimate Efficiency Limit



Ultimate efficiency limit for thermionic converters:

Φ_{in} / electron $= \Phi_e$

$\longrightarrow \quad \eta = \Phi_{out} / \Phi_{in} = 1 - \Phi_c / \Phi_e$

Φ_{out} / electron $= \Phi_e - \Phi_c$

Comparison with Photovoltaics, Thermoelectrics

Efficiency of PV and thermoelectrics is limited well below Carnot:

- PV: bandgap, Shockley-Queisser
- thermoelectrics: simultaneously small κ and large σ

Projected Maximal Efficiencies

combined cycles

$\phi_c \sim 1.4$ eV

$T_e = 1700$ °C, $\phi_e = 3.1$ eV

1400 °C, 3.0 eV, PETE

te generators

$\phi_e = 2.7$ eV, $\phi_c = 0.9$ eV

$T_e = 1200$ °C, PETE

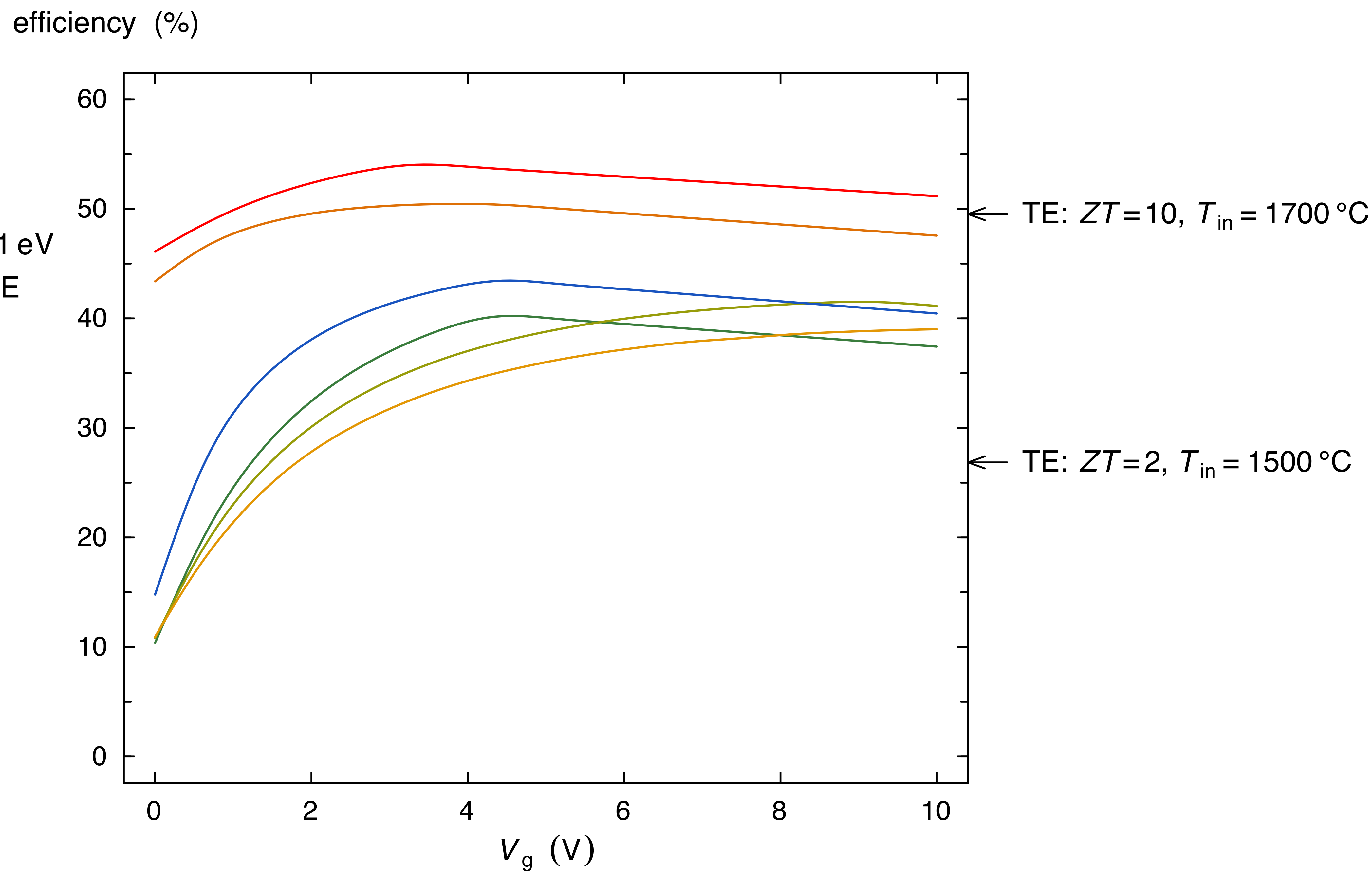
1500 °C

1600 °C

1700 °C

$T_c = 200$ °C

$d_{ec} = 30$ µm



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Key Issues: Emitter and Collector

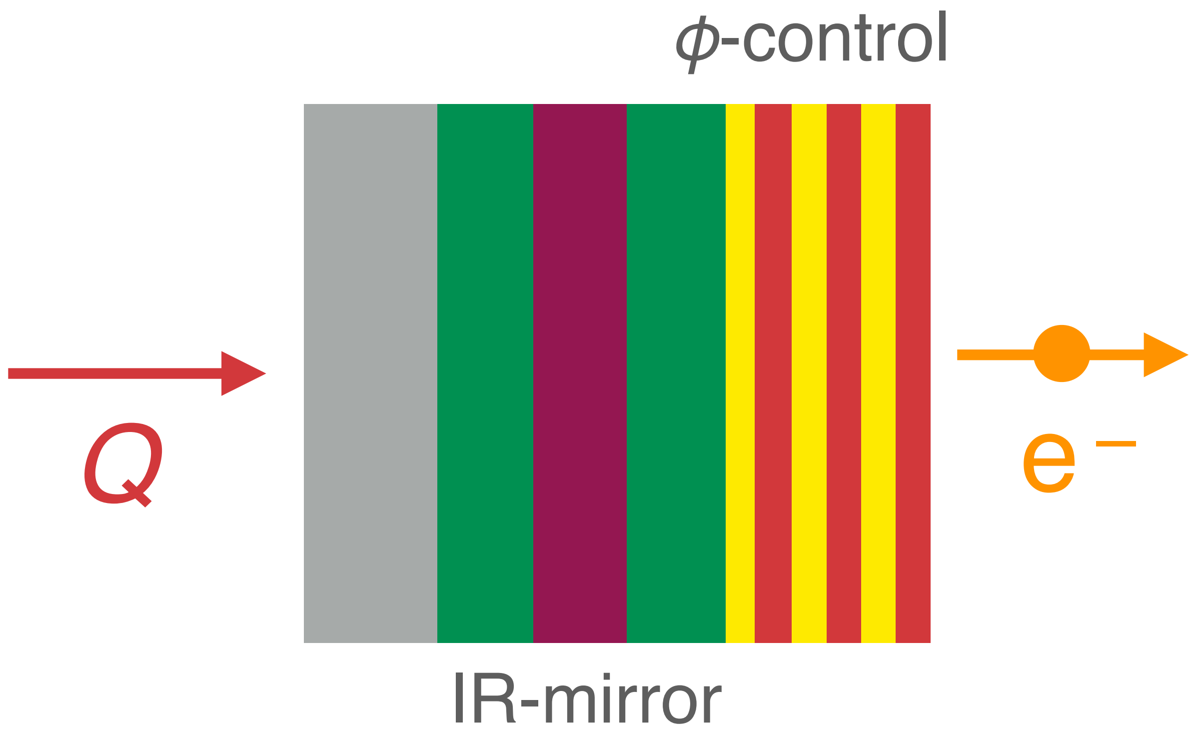
Requested:

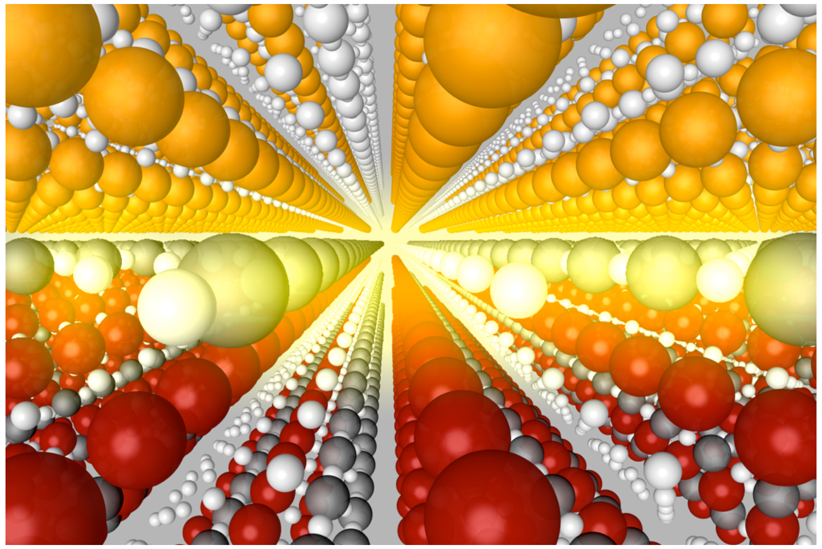
- optimized work functions for *E* and for *C*
- small IR-emissivity ε
- inertness at high *T*

- need for materials with designed work functions (diamonds?), heterostructures
- nano-tailored surfaces (nanotips? nanotubes?)
- novel electron emission and collection schemes

sizable potential

Heterostructure-based Emitter and Collector





Future Research Needs and Directions

(1) optimization of E, C, G materials, their nanostructures, IR-parameters, electron emission and collection processes

(2) study, enhancement of long-time stability in working atmosphere

(3) exploration of roads to *B*-reduction

(4) device engineering, loss reduction, system integration

- **all problems we see are technological, no roadblock from physics**
- **no fundamental limit to efficiency well below Carnot, such as Shockley-Queisser**