

The Franck-Hertz experiment: 100 years ago and now

A tribute to two great German scientists

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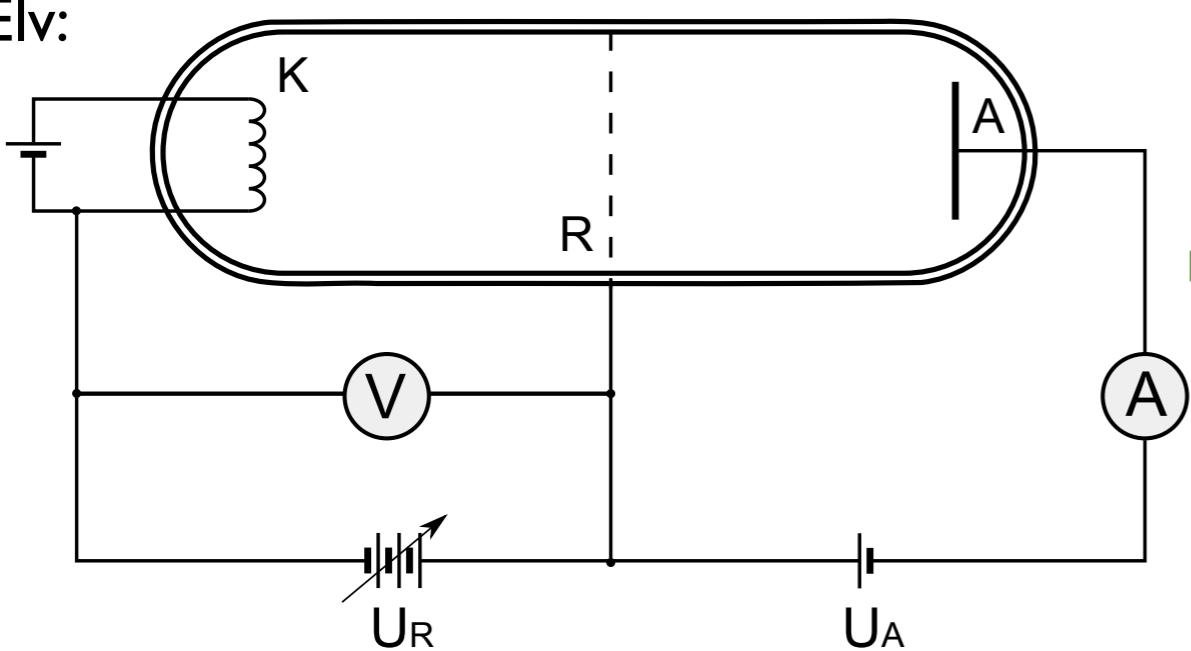
Franck-Hertz experiment anno (~1914)

The Nobel Prize in Physics 1925 was awarded jointly to James Franck and Gustav Ludwig Hertz "for their discovery of the laws governing the impact of an electron upon an atom"



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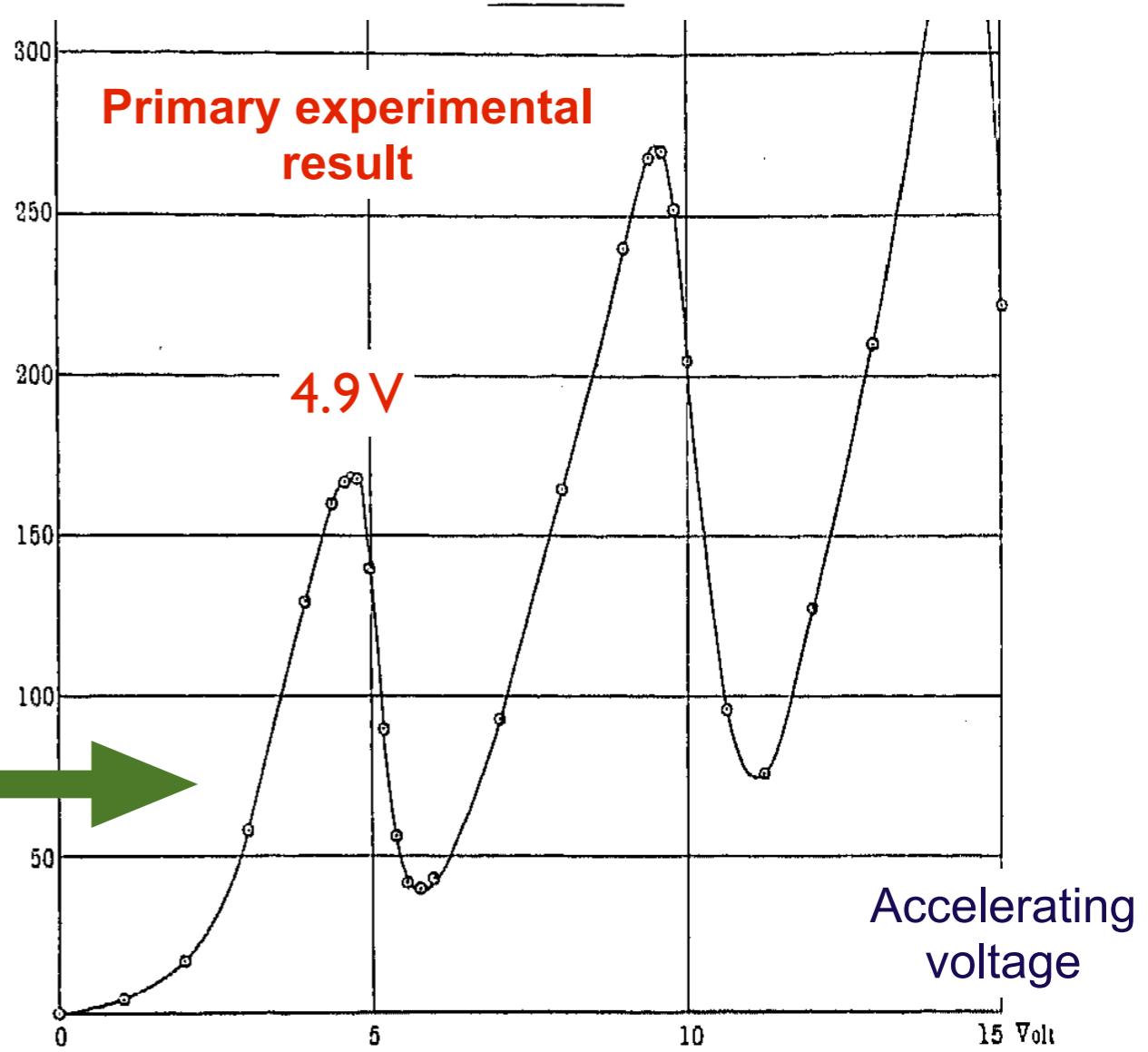


Über Zusammenstöße zwischen Elektronen und den Molekülen des Quecksilberdampfes und die Ionisierungsspannung desselben;
von J. Franck und G. Hertz.

(Vorgetragen in der Sitzung vom 24. April 1914.)

(Vgl. oben S. 393.)

Anode current



Verh. Dtsch. Phys. Ges. 16: 457–467 (1914).

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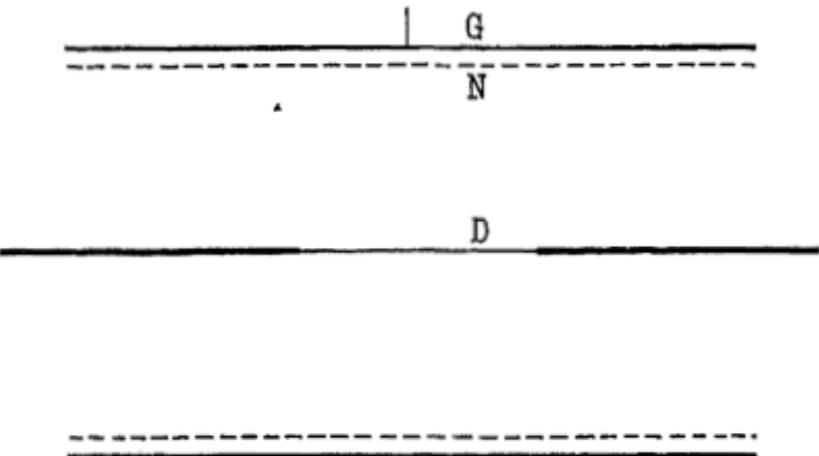
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und kleiner Feldstärke zu erwarten war. Der sowohl zu diesen Versuchen, als auch zur endgültigen Messung der Ionisierungsspannung verwandte Apparat ist in der Fig. 1 dargestellt¹⁾. *D* ist ein Platindraht, dessen mittleres Stück dünner ist und durch einen elektrischen Strom zum Glühen gebracht werden kann. *N* ist ein feines Platindrahtnetz, welches den Draht *D* im Abstand von 4 cm zylindrisch umgibt, und *G* eine zylindrische Platinfolie, welche von *N* einen Abstand von 1 bis 2 mm hatte. *G* war

Fig. 1.



durch ein Galvanometer mit der Erde verbunden. Durch in die Oberfläche des Glases eingeschmolzene Ringe aus Platinfolie war verhindert, daß von den spannungsführenden Teilen Ströme über das Glas zum Galvanometer fließen konnten. Außer Glas und Platin enthielt der Apparat keine festen Bestandteile. Alle Zuleitungen waren in das Glas eingeschmolzen.

Während der Messung befand sich der Apparat in einem elektrisch geheizten Paraffinbad. Mit der während der Messungen dauernd laufenden Pumpe war er durch ein enges U-Rohr verbunden, das sich ebenfalls im Heizbad befand und an seinem tiefsten Punkt einen mit Quecksilber gefüllten Ansatz hatte. Da sich außerdem im unteren Teil des eigentlichen Apparates ein

Franck-Hertz experiment anno (~1914)

1914.]

Über Zusammenstöße zwischen Elektronen usw.

467

Zusammenfassung.

1. Es wird gezeigt, daß die Elektronen im Quecksilberdampf elastische Zusammenstöße mit den Molekülen erleiden, bis zu einer kritischen Geschwindigkeit.

2. Es wird ein Verfahren beschrieben, diese kritische Geschwindigkeit auf ein Zehntel Volt genau zu messen. Sie ist gleich der Geschwindigkeit, die Elektronen besitzen, die 4,9 Volt durchlaufen haben.

3. Es wird gezeigt, daß die Energie eines 4,9-Voltstrahles genau gleich einem Energiequantum der Quecksilberresonanzlinie $253,6 \mu\mu$ ist.

4. Es werden die Gründe dafür diskutiert, daß bei der Energieabgabe der 4,9-Voltstrahlen an die Quecksilbermoleküle ein Teil der Stöße zur Ionisation führt, so daß 4,9 Volt die Ionisierungsspannung des Quecksilberdampfes wäre. Ein anderer Teil der Stöße scheint Licherregung hervorzurufen, von der wir vermuten, daß sie in der Emission der Linie $253,6 \mu\mu$ besteht¹⁾.

Ein Teil der verwandten Apparate, sowie das benutzte Platin ist aus Mitteln der SOLVAY-Stiftung angeschafft, wofür wir unseren besten Dank auszusprechen haben.

Berlin, den 5. Mai 1914. Physik. Institut der Universität.

¹⁾ Anmerkung bei der Korrektur (16. Mai): Wir haben unterdes Versuche angestellt, um die Anregung der Linie $253,6 \mu\mu$ durch 4,9 Volt-Strahlen nachzuweisen, die in der Tat ein positives Resultat ergaben; wir werden darüber im nächsten Heft der Verhandlungen berichten.

"The electrons in Hg vapor experience only elastic collisions up to a critical velocity"

"We show a method using which the critical velocity (i.e. the accelerating voltage) can be determined to an accuracy of 0.1 V; its value is 4.9 V."

"We show that the energy of the ray with 4.9 V corresponds to the energy quantum of the resonance transition of Hg ($\lambda = 253.6 \text{ nm}$)"

(("Part of the energy goes into excitation and part goes into ionization"))

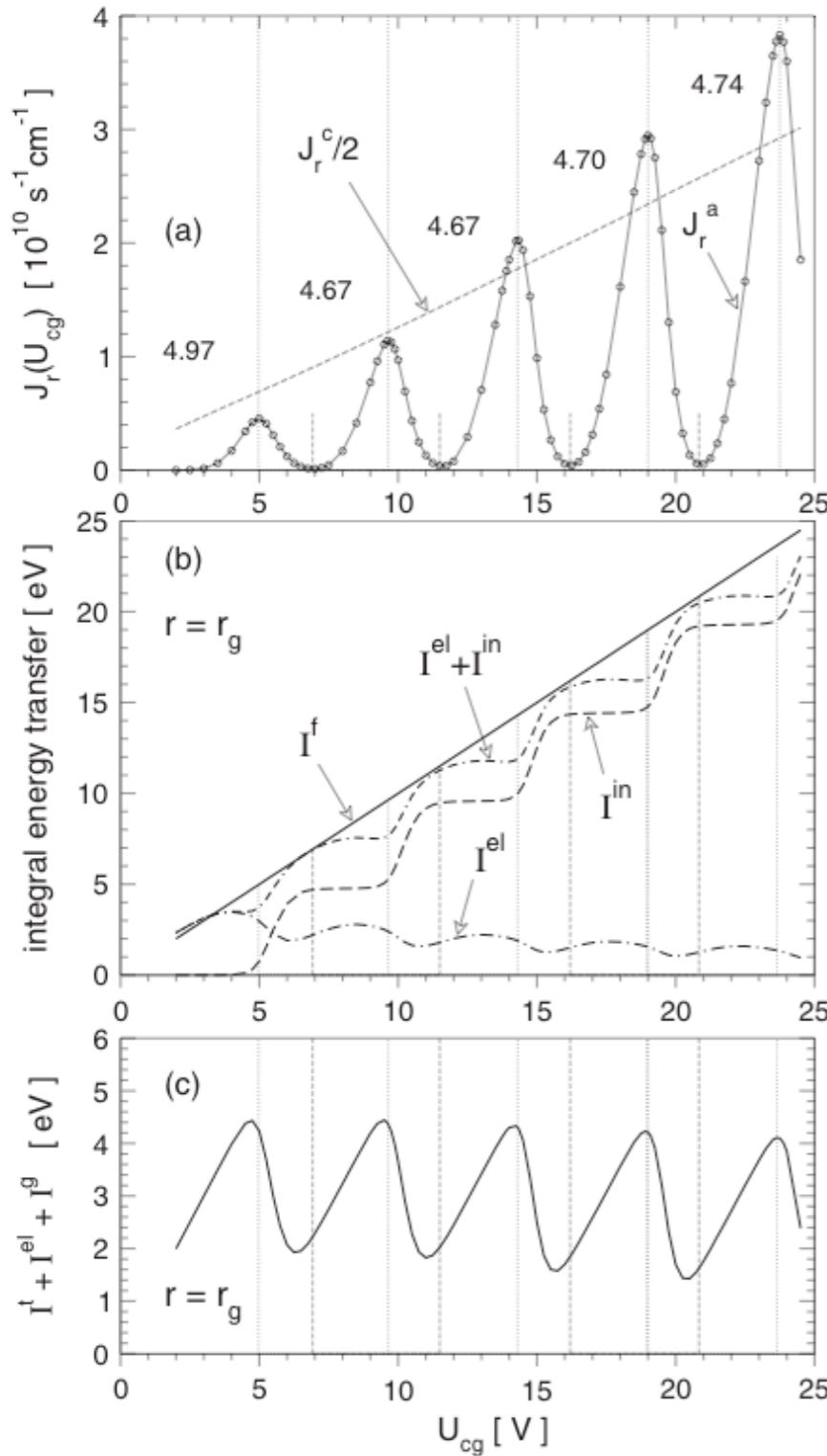
Important experimental evidence for the quantized nature of the atomic energy levels.

The Franck-Hertz experiment: 100 years ago and now

- ▶ Franck-Hertz experiment: published in 1914, Nobel prize in 1925
- ▶ Why is it interesting today as well?
 - ▶ “Simple” explanation (“The electrons”) → description based on kinetic theory (Robson, Sigeneger, ...)
 - ▶ Modern experiments
 - ▶ Various gases (Hg, He, Ne, Ar)
 - ▶ Modern experiment **+** kinetic description (develop an experiment that can be modeled accurately ...) → P. Magyar, I. Korolov, Z. Donkó: "*Photoelectric Franck-Hertz experiment and its kinetic analysis by Monte Carlo simulation*" Phys. Rev. E 85, 056409 (2012).

Franck-Hertz experiment: Boltzmann eq. analysis

Contrib. Plasma Phys. **43**, No. 3-4, 178–197 (2003) / DOI 10.1002/ctpp.200310014

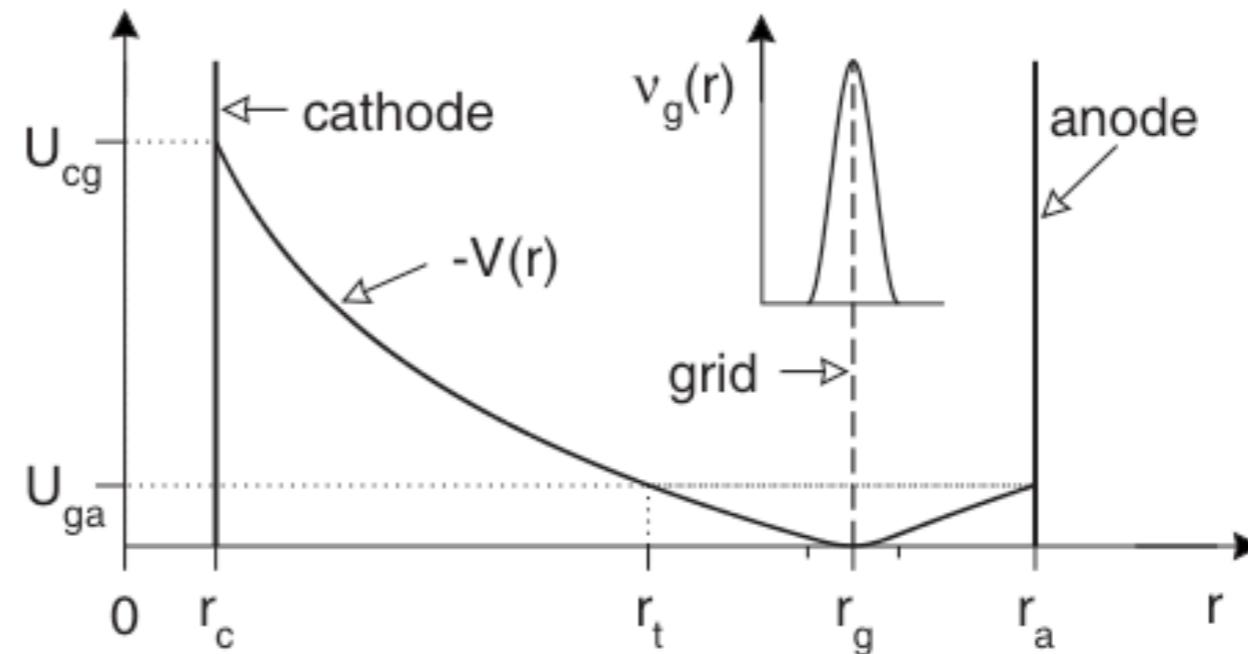


What really happens with the electron gas in the famous Franck-Hertz experiment?

F. Sigeneger^{*1}, R. Winkler¹, and R. E. Robson²

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² Research School of Physical Sciences, Australian National University, Canberra, A.C.T. 2600



- ▶ Solution of the Boltzmann equation (1D)
- ▶ Most accurate theoretical description so far - however, without new experiment
- ▶ Homogeneous Hg vapor density (!!)
- ▶ Grid : “loss frequency” (!!)

Franck-Hertz experiment: modern interpretation

ATOMPHYSIK

Physik Journal 13 (2014) Nr. 3

Ein Grundstein der Atomphysik

Die gängige Lehrbuchinterpretation des Franck-Hertz-Experiments lässt viele Fragen offen.

Robert E. Robson, Malte Hildebrandt und Ronald D. White



need kinetic theory to explain
and understand observations

Das Franck-Hertz-Experiment aus dem Jahre 1914 fehlt in keinem Lehrbuch, zeigt es doch anschaulich die quantisierten Eigenschaften der Atome und legt damit den Grundstein für die moderne Atomphysik. Allerdings versagt die traditionelle Interpretation, wenn mehrere angeregte Niveaus ins Spiel kommen. Nur eine Analyse aus dem Blickwinkel der elementaren kinetischen Gastheorie erlaubt es, den korrekten Zusammenhang zwischen mikroskopischen Vorgängen, die den Gesetzen der Quantenmechanik unterliegen, und den im Labor gemessenen makroskopischen Größen herzustellen.

Die bedeutenden Experimente des späten 19. und frühen 20. Jahrhunderts zur Untersuchung von elektrischen Strömen in Gasen leiteten eine neue Epoche in der Geschichte der modernen Physik ein.

AIP Emilio Segré Visual Archives, Born Collection



James Franck (1882 – 1964, links) und Gustav Hertz (1887 – 1975) begegneten sich 1911 am Physikinstitut der Friedrich-



Wilhelms-Universität Berlin, wo sie ihr bahnbrechendes Experiment durchführten.

A.B. Lagerius & Westphal / AIP Emilio Segré Visual Archives

The Franck-Hertz experiment: 100 years ago and now

Experimental apparatus, experimental results

Simulation of the electrons' motion in electric field (basics, FH cell model)

Simulation results and comparison with experimental data

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A simple (??) experiment

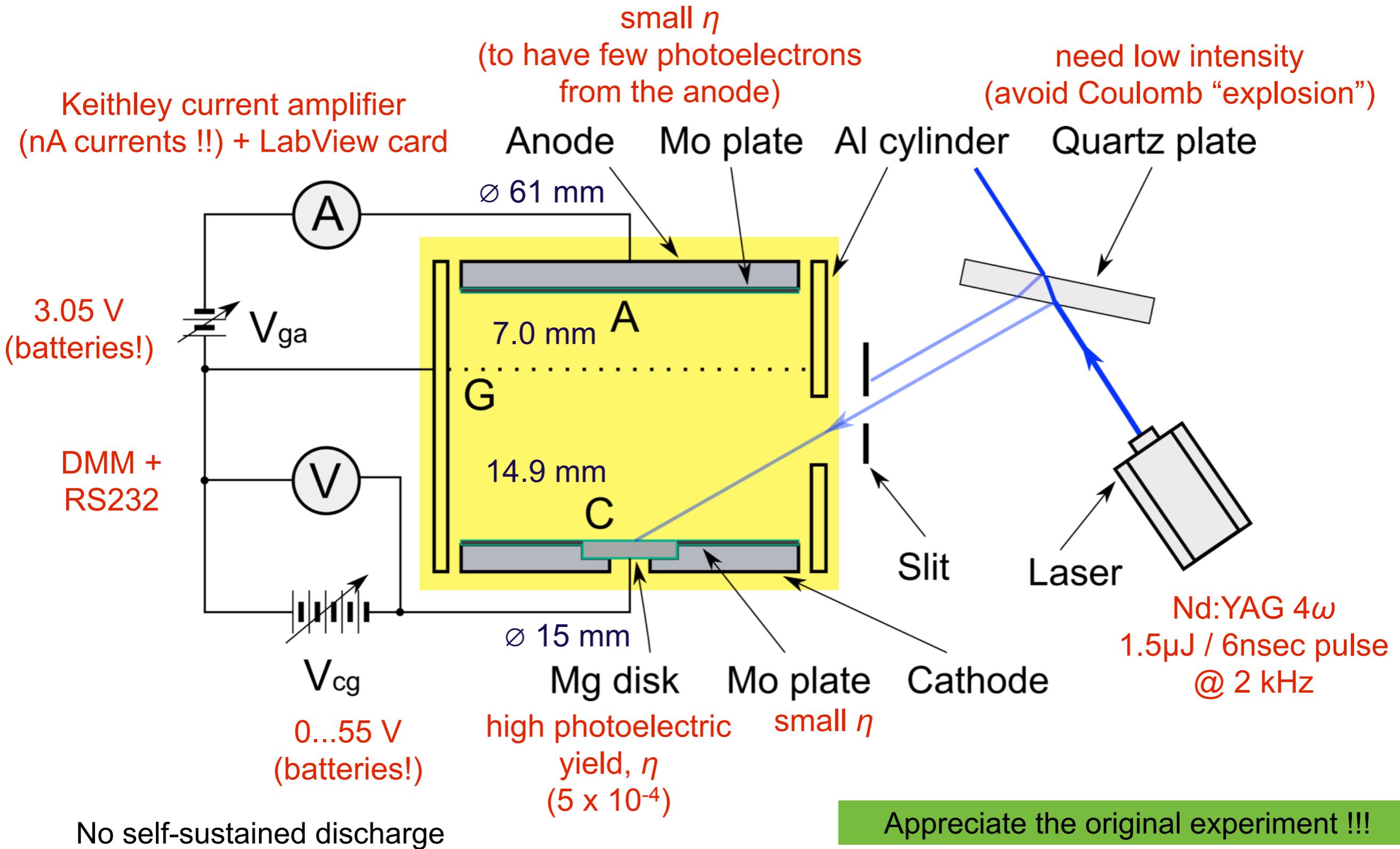
Thanks:

Péter Hartmann
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Kinga Kutasi
Aranka Derzsi
Judit T. Forgács
József Tóth
György Császár
Elek Sárközi



- ▶ Heating / photoemission ?
- ▶ Material for photocathode (Na / ??)
- ▶ Illumination (Hg lamp / 400 nm laser / ??)
- ▶ Easy to model cell geometry !
- ▶ Radial / axial construction ?
- ▶ Glass envelope / metal vacuum chamber ?

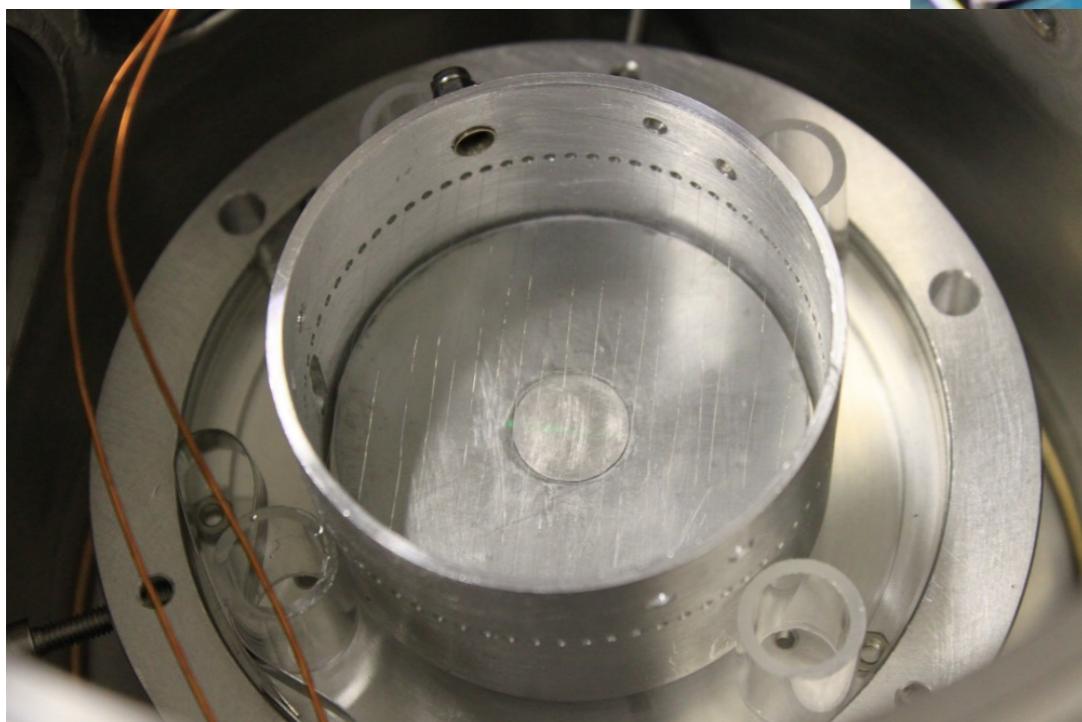
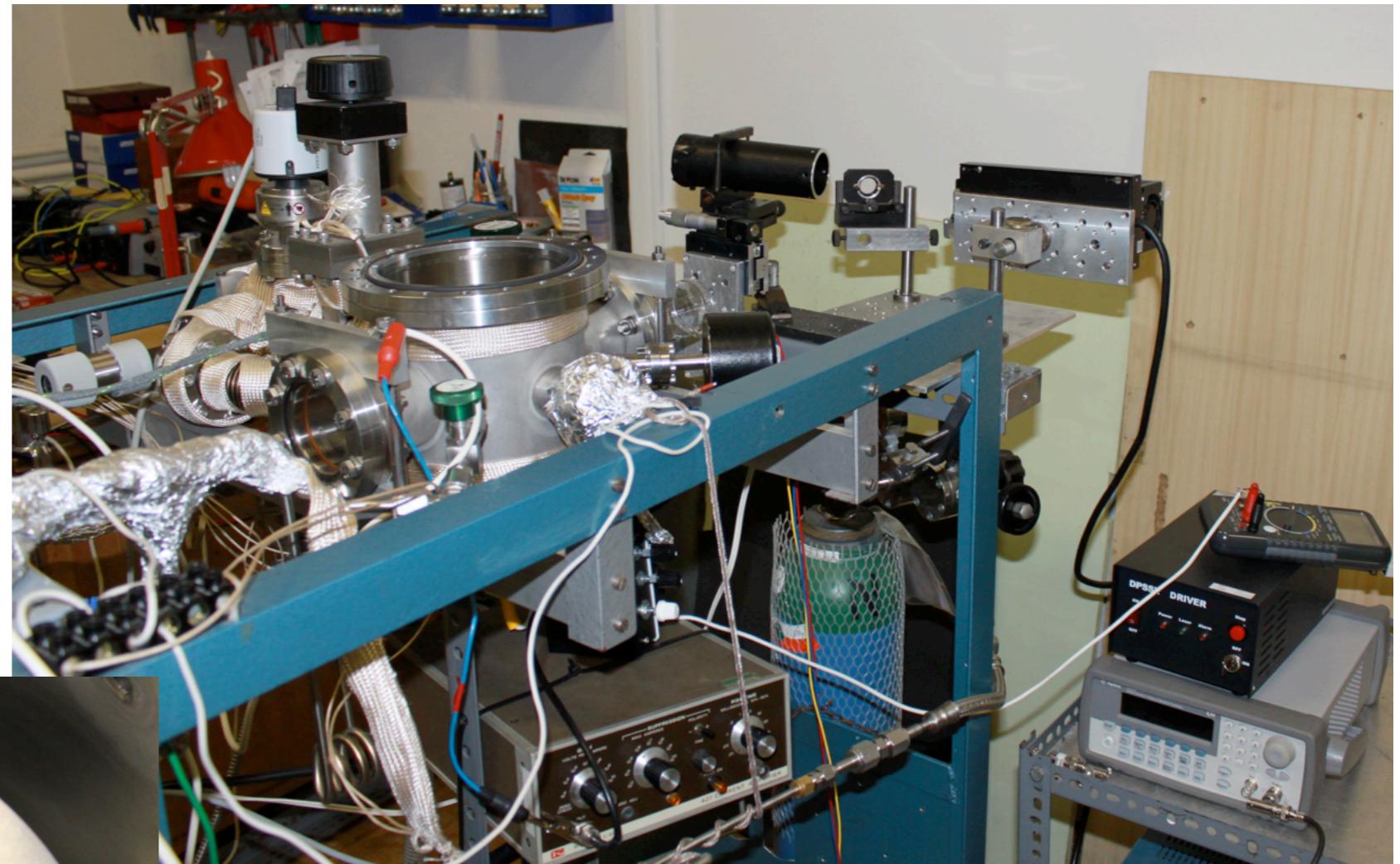
Experimental setup



Experimental setup

Vacuum system:

- ▶ Rotary + turbo pumps
- ▶ $p_0 \sim 10^{-7}$ mbar
- ▶ Heating (~ 100 °C)
- ▶ Argon 6.0
- ▶ Flowing gas + liquid nitrogen trap



FH cell:

- ▶ Ultrasonic cleaning in ethanol

Control of
measurements:

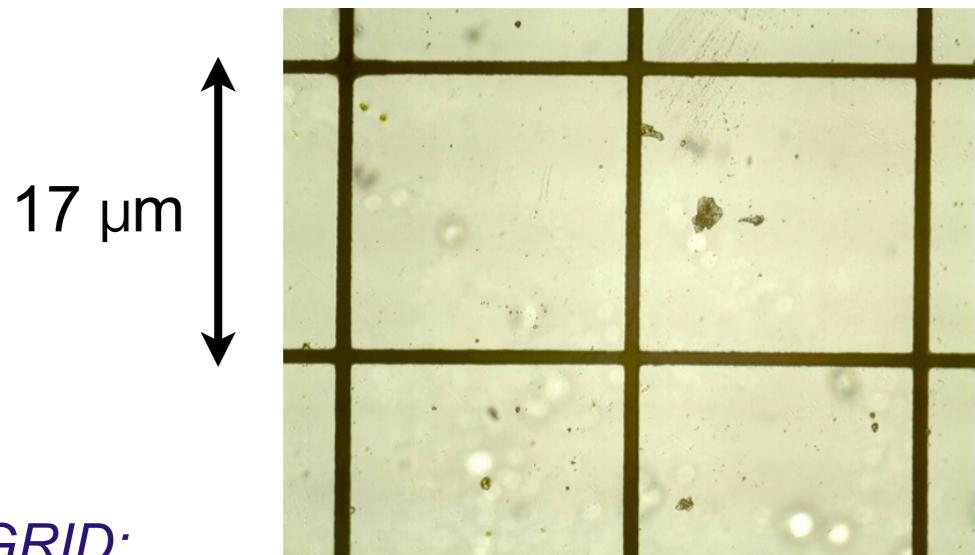
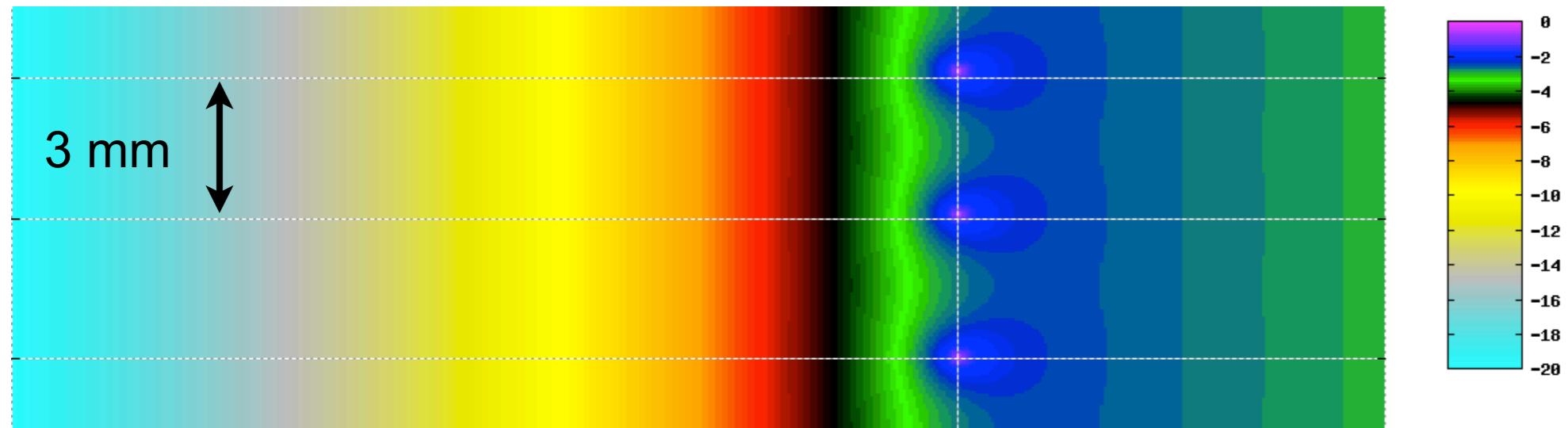
- ▶ LabView (I. K.)

The grid

$V_c = -20V$

$V_g = 0V$

$V_a = -3V$



GRID:

- ▶ Ni mesh / Precision Eforming Co.
- ▶ T = 90 %
- ▶ “wires” 17 μm , 70 / inch (~0.36 mm)



The grid plane is not an equipotential surface;
for the above conditions we have ~3 V modulation
that smoothes the FH characteristics

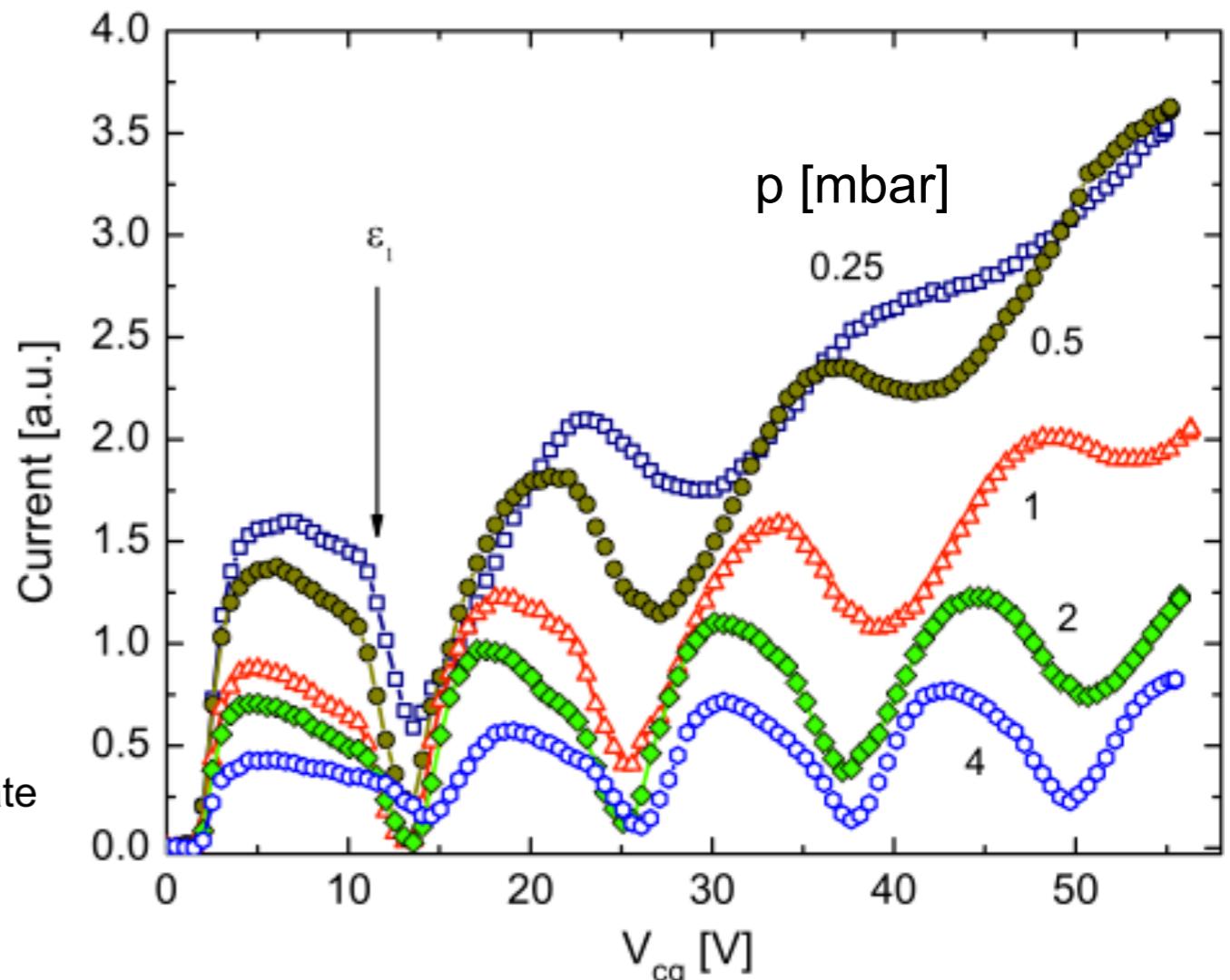
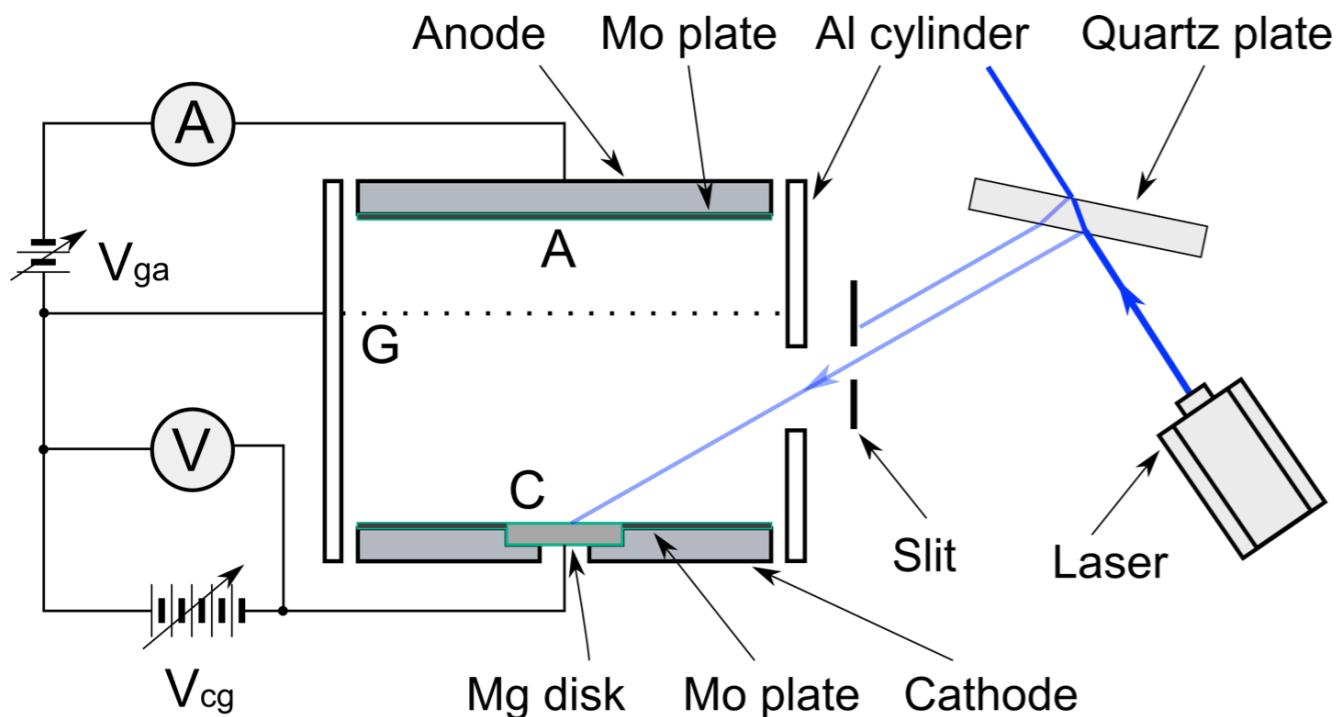


We need a “**FINE**” mesh in
the experiment, with a
HIGH* transmission

(* why? - see later)

Measured FH characteristics

- ▶ High pressure: Strong modulation, nearly periodic characteristics - excitation to low-lying levels of Ar only
- ▶ Medium pressure: higher slope, decreasing modulation, probably due to a wider electron energy distribution, caused by excitations to several levels
- ▶ Low pressure: only few peaks, high slope, due to ionizing collisions



$p : 0.25 \text{ mbar} \dots 4 \text{ mbar (16x)}$

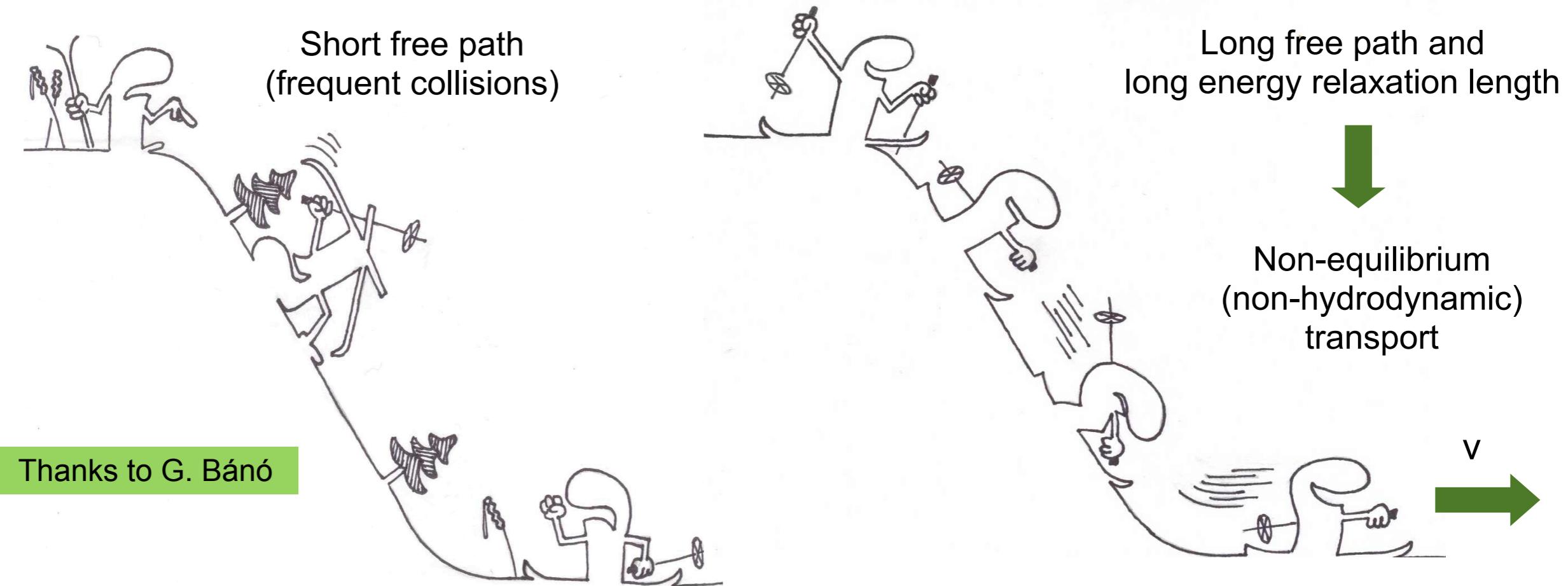
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Equilibrium / non-equilibrium transport



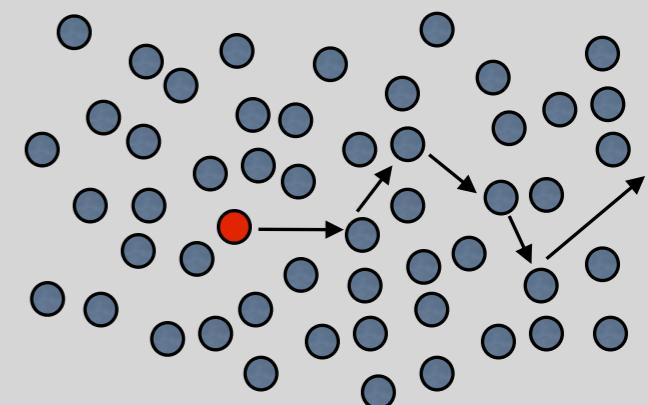
Boltzmann
equation

KINETIC THEORY

Particle-based
simulation

$$\left[\frac{\partial}{\partial t} + \mathbf{a} \cdot \nabla_{\mathbf{v}} + \mathbf{v} \cdot \nabla_{\mathbf{r}} \right] f = \left(\frac{\partial f}{\partial t} \right)_{\text{coll}}$$

$f = f(\mathbf{r}, \mathbf{v}, t)$
Velocity distribution
function



Tracing electrons by Monte Carlo simulation

Tracing of a single particle (cold gas approx.)

Equation of motion: $m \frac{d^2\mathbf{r}}{dt^2} = e\mathbf{E}$



$$t \rightarrow t + \Delta t$$

Probability of collision: $P_{\text{coll}} = 1 - e^{-n\sigma v \Delta t}$

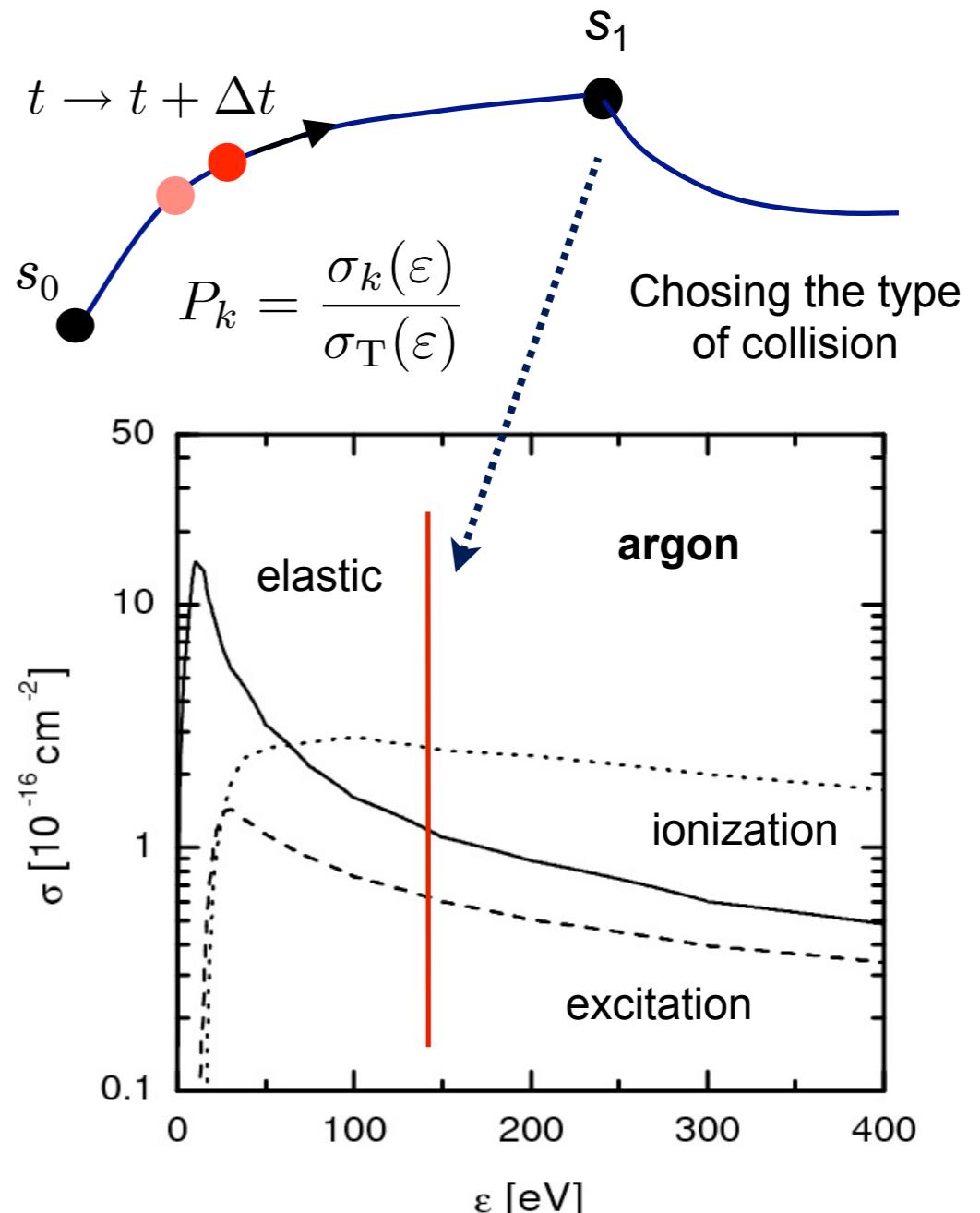
Total cross section

Processes:

- ▶ elastic scattering
- ▶ excitation
- ▶ ionization

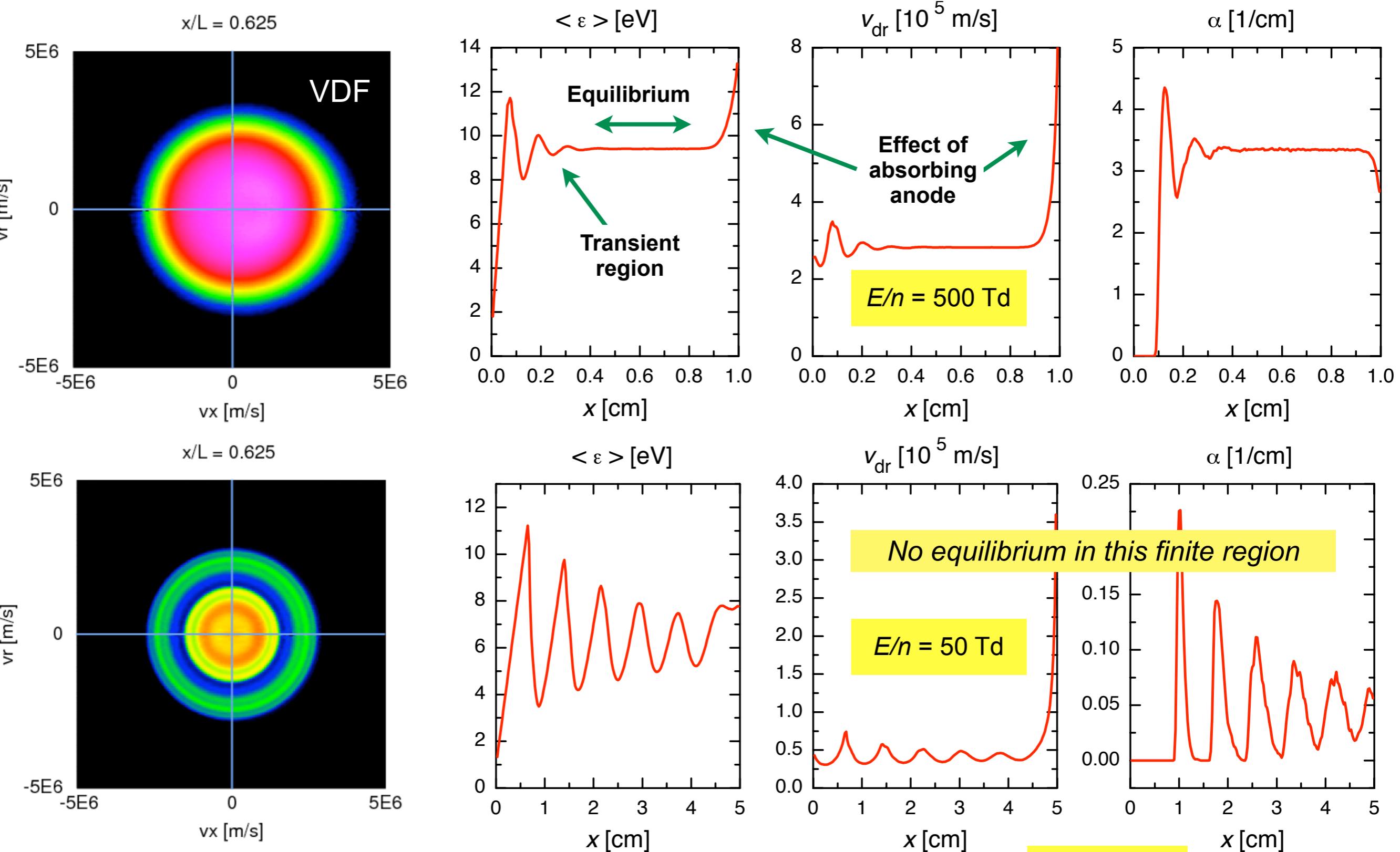
Quantities chosen in a probabilistic manner:

- ▶ length of free path
- ▶ type of collision
- ▶ direction of post-collision velocity



Apply this method to a plane-parallel electrode configuration / homogeneous electric field :
HOW DOES THE VDF BEHAVE?

Motion of electrons in homogeneous electric field



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Simulation model of the Franck-Hertz cell

- ▶ Potential distribution with cylindrical symmetry

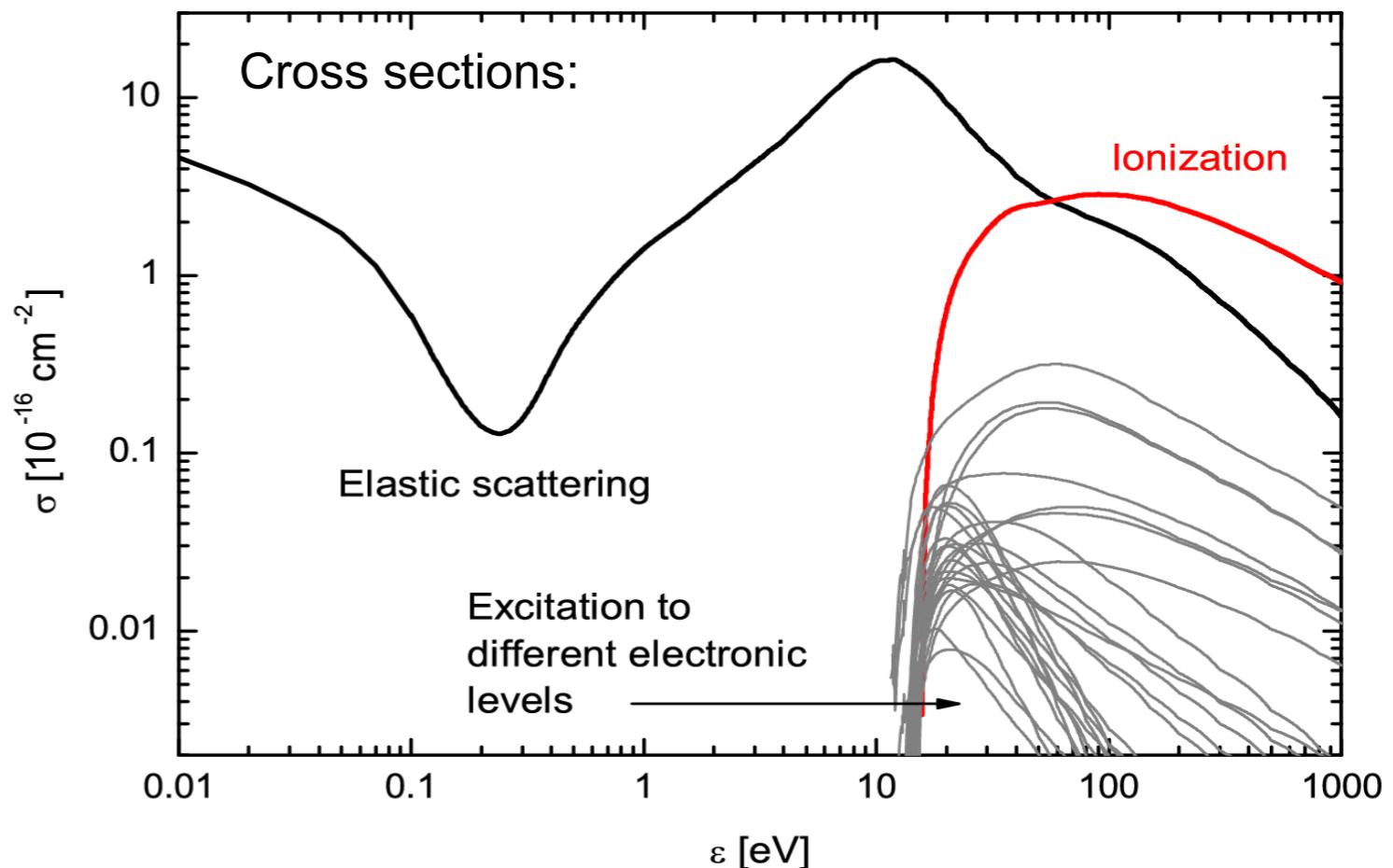
$$U = U(x, r)$$

- ▶ The plane of the grid is equipotential surface
- ▶ Monte Carlo simulation, tracing 10^5 photoelectrons (+ secondaries) for each parameter combination
- ▶ $T = 300 \text{ K}$
- ▶ Reflection / absorption on walls and electrodes:

$$R(\Theta) = R_0 \exp[c(1 - \cos \Theta)]$$

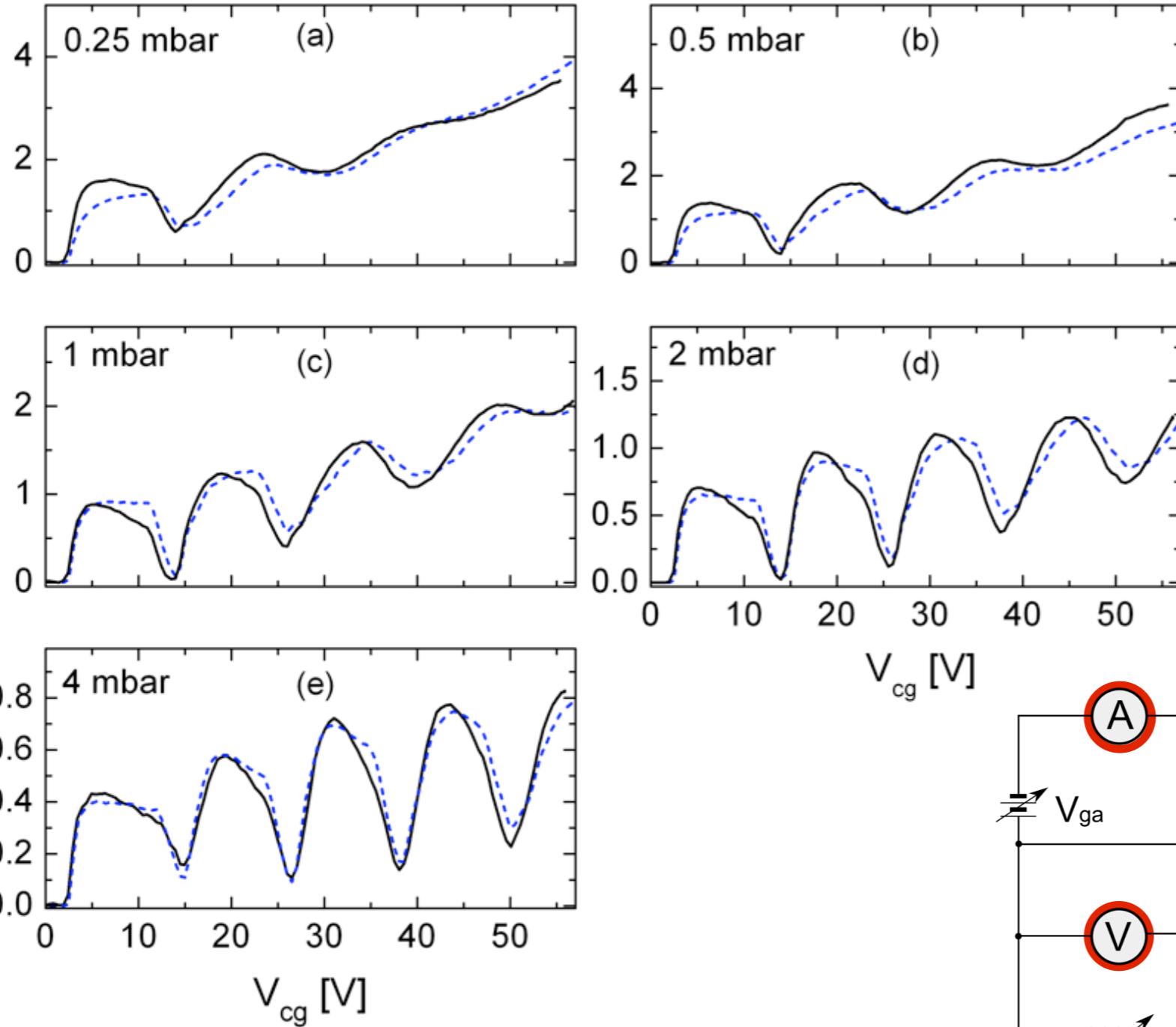
- ▶ $R_0 = 0.7$ (in perpendicular case)
- ▶ Electrons are transmitted through the grid with a probability equal to the geometrical transmittance; otherwise they are elastically reflected

The regions in the FH cell are too short for an equilibrium transport to develop.
 Non-equilibrium transport → kinetic description:
 MC simulation

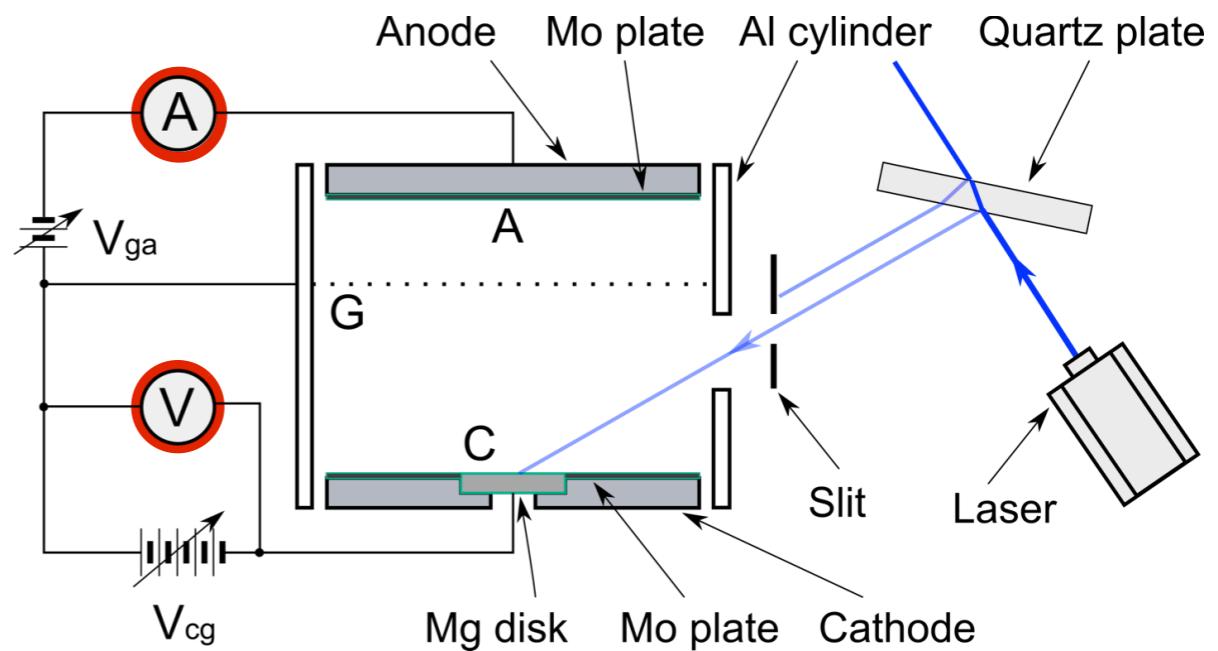


Hayashi M 2003 *Bibliography of Electron and Photon cross sections with Atoms and Molecules Published in the 20th Century: Argon NIFS-DATA-72*, National Institute for Fusion Science (Jpn), ISSN 0915-6364

Comparison of experimental and simulation results

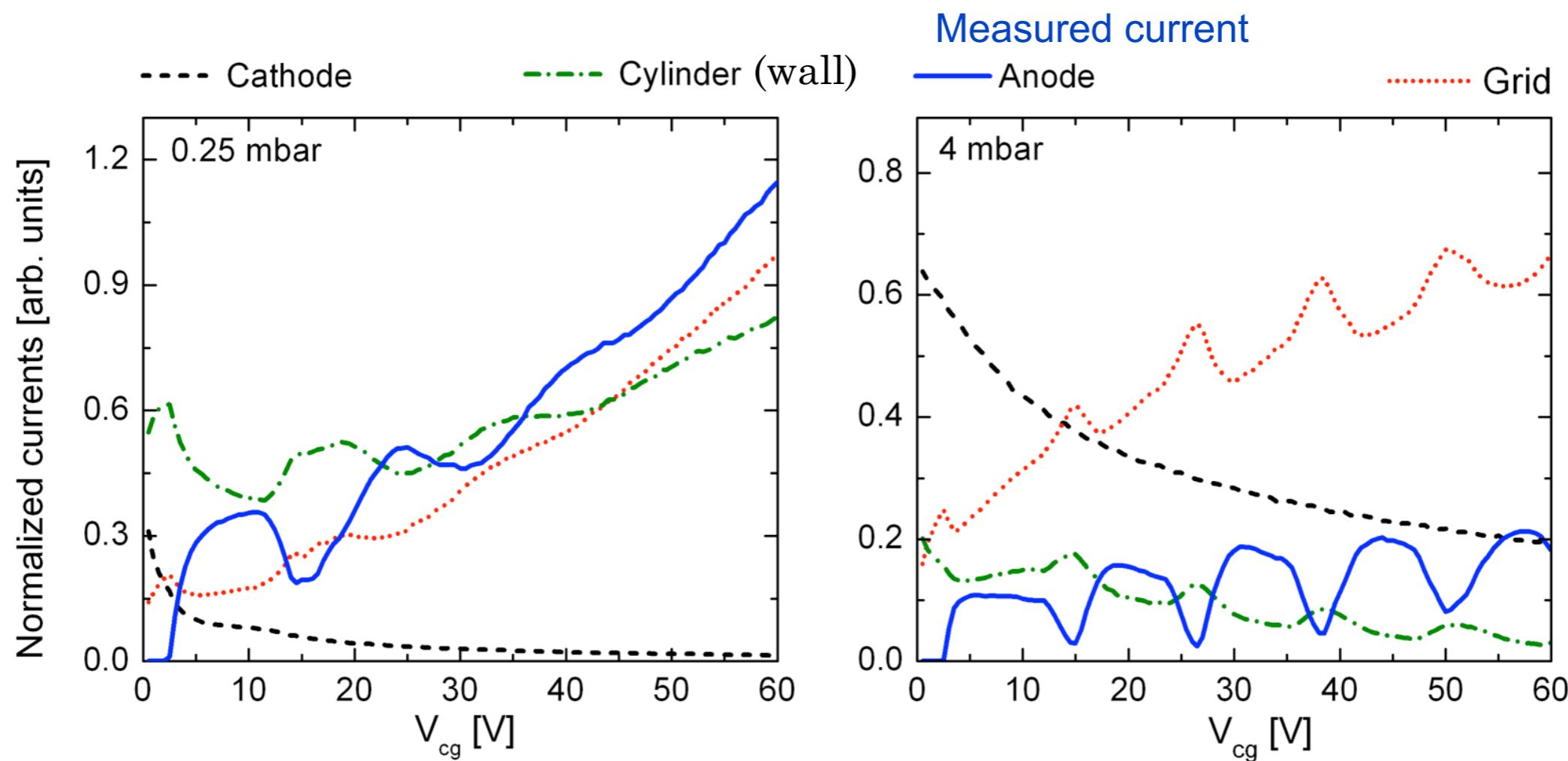


The experimental and simulation results have to be scaled (both are measured in relative units) - but we use the *same scaling factor* for all the different pressure values.

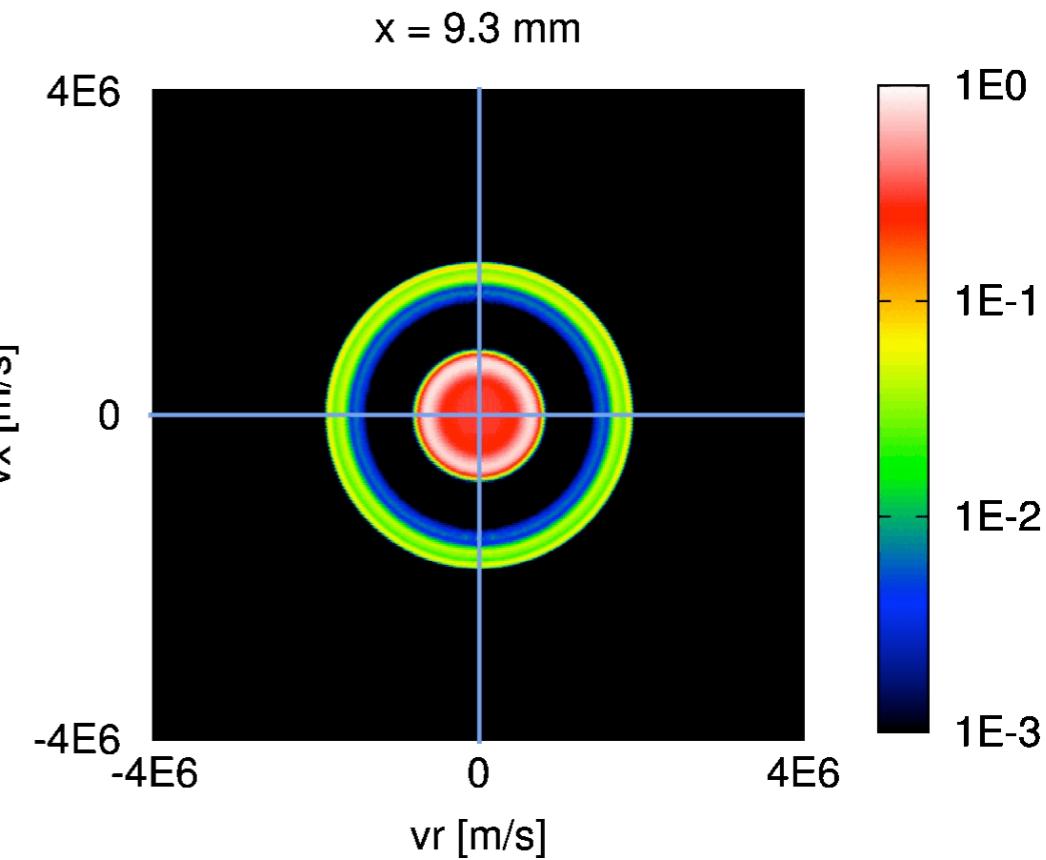
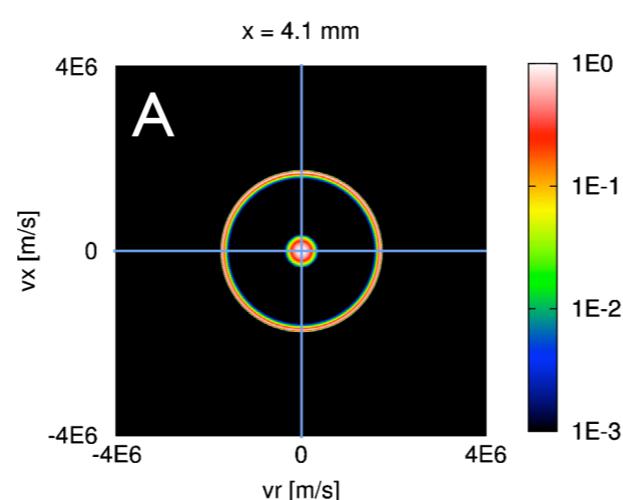
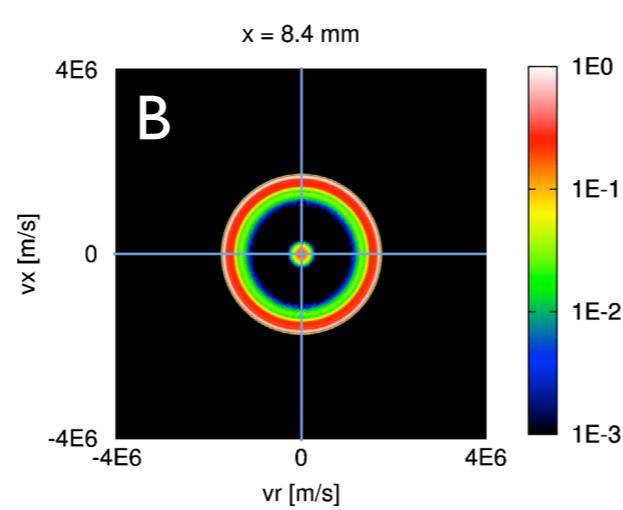
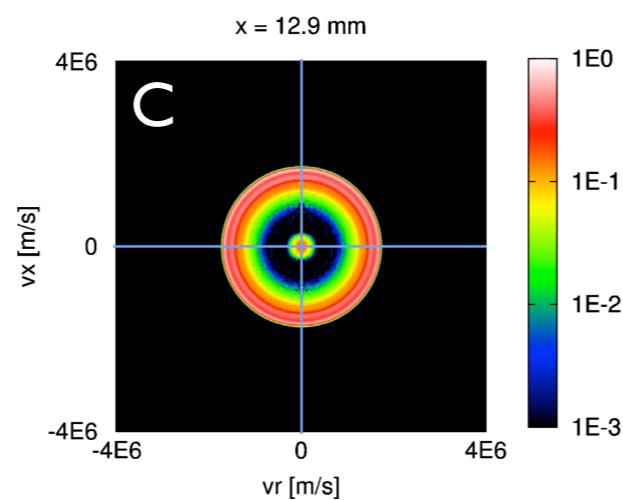
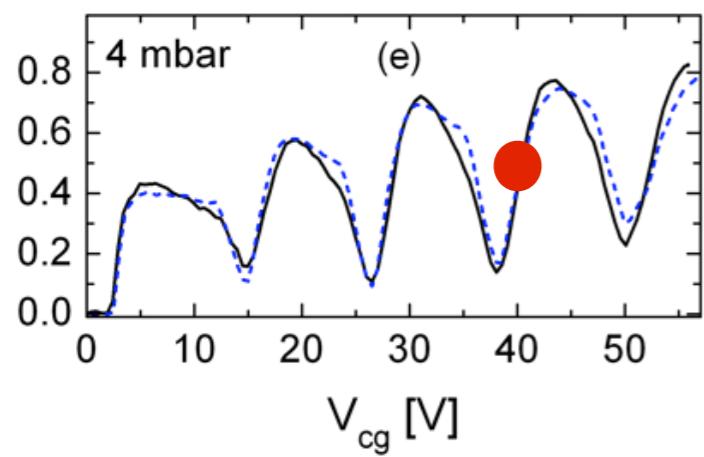
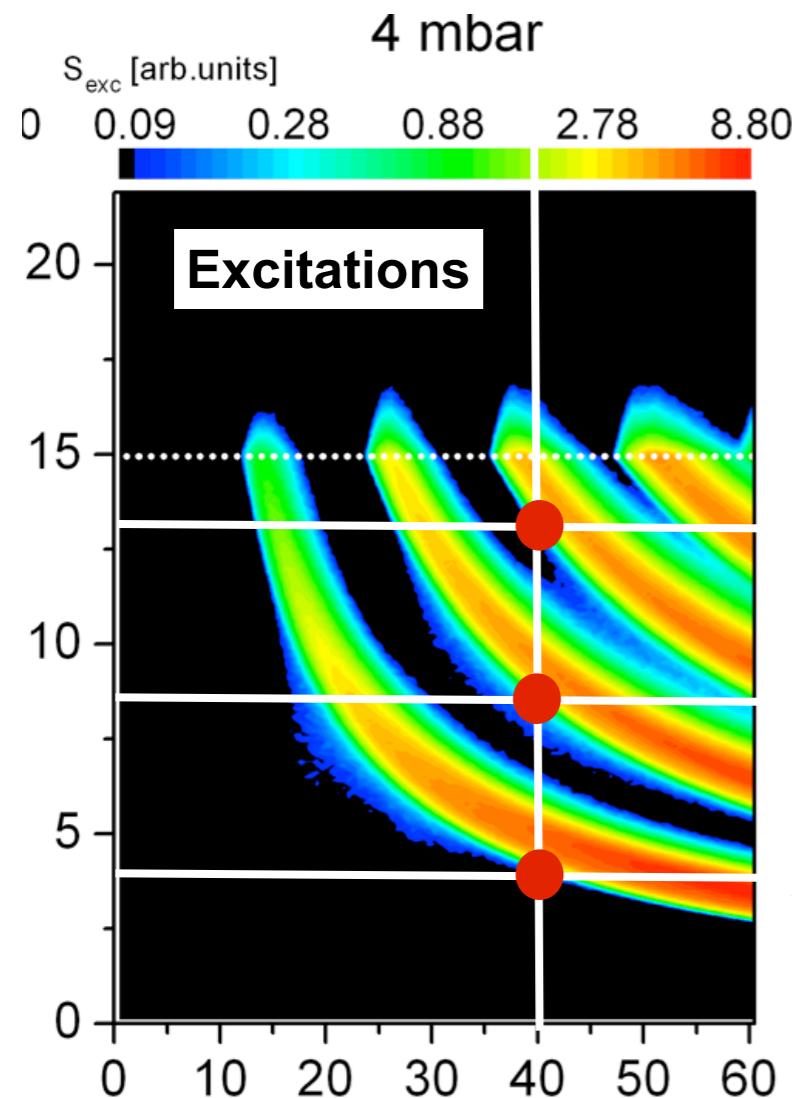


Simulation results: currents

- ▶ A large part of photoelectrons is backscattered to the cathode and is absorbed, especially at low E/n values (4 mbar, low accelerating voltage). At the highest E/n values this portion becomes negligible.
- ▶ The current reaching the grid changes in opposite phase with respect to the anode current.
- ▶ The current reaching the wall behaves similarly, its value is appreciable, especially at lower pressures - 2D nature of the model is important.

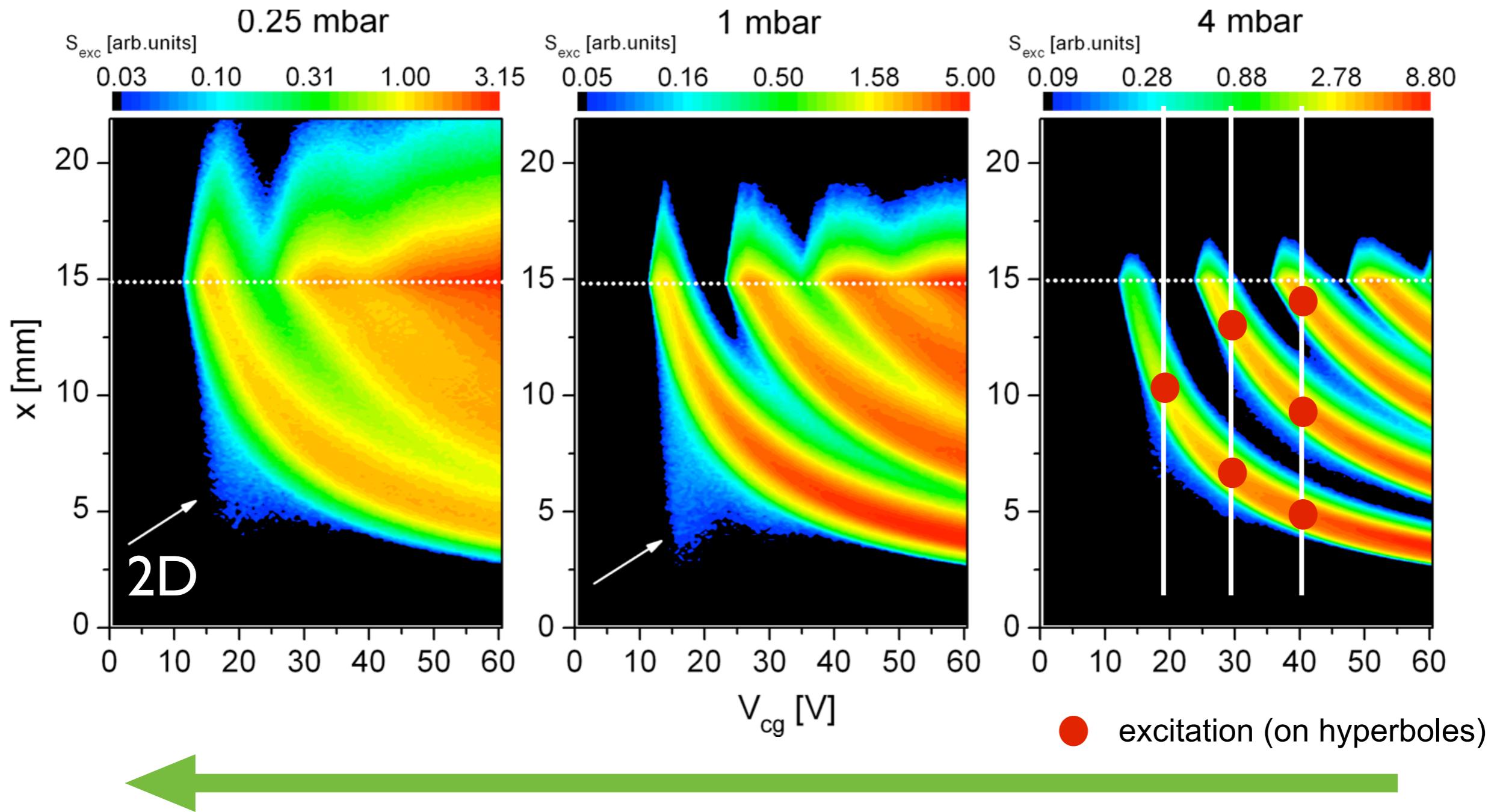


The VDF of electrons



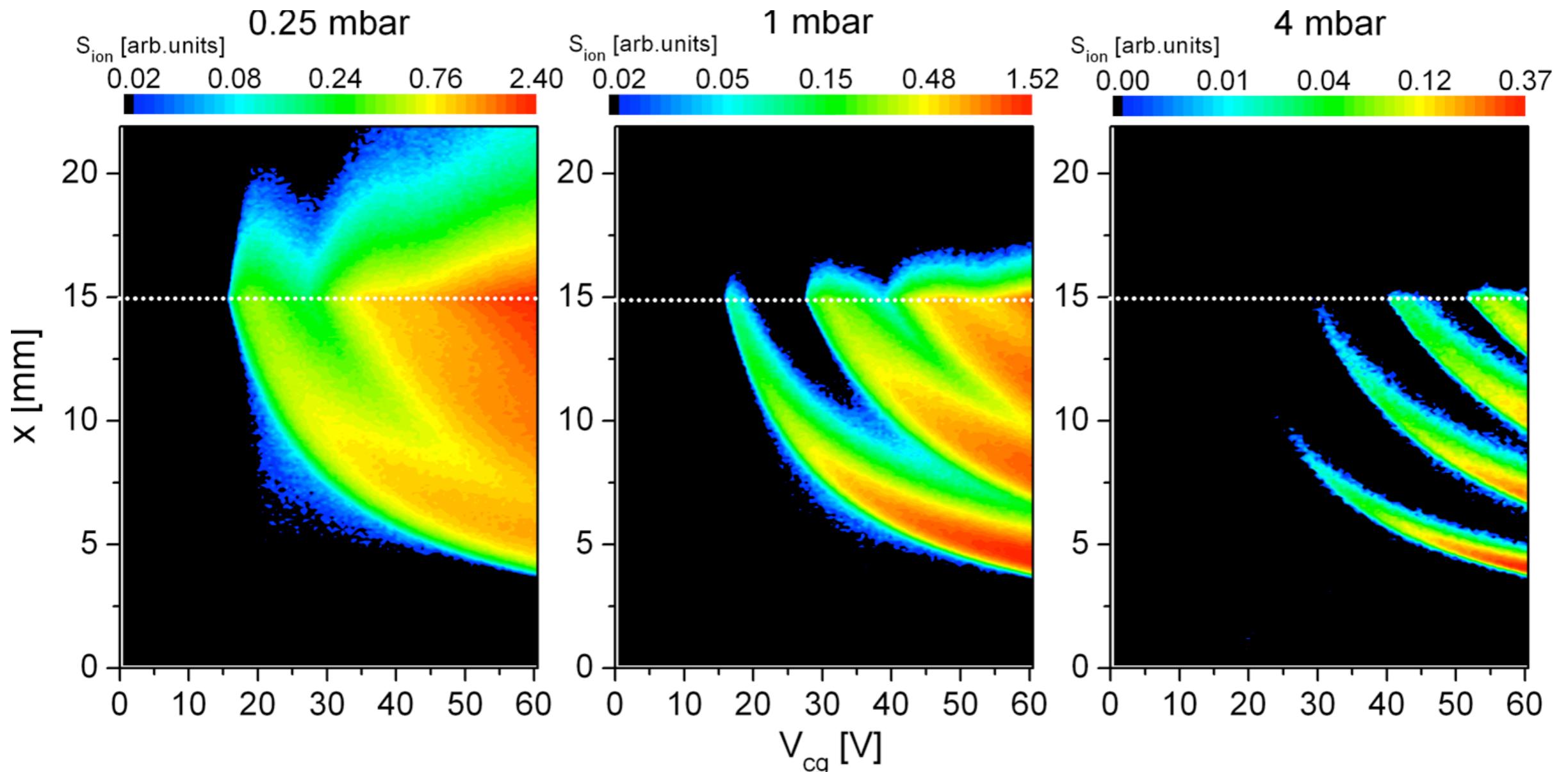
- $V_{\text{cg}} = 40 \text{ V}$
- $p = 4 \text{ mbar}$
- The VDF is nearly isotropic for most of the conditions
(\rightarrow electrons cross the grid plane several times \rightarrow need high transmission in the experiment!)

Spatial distribution of excitation rate

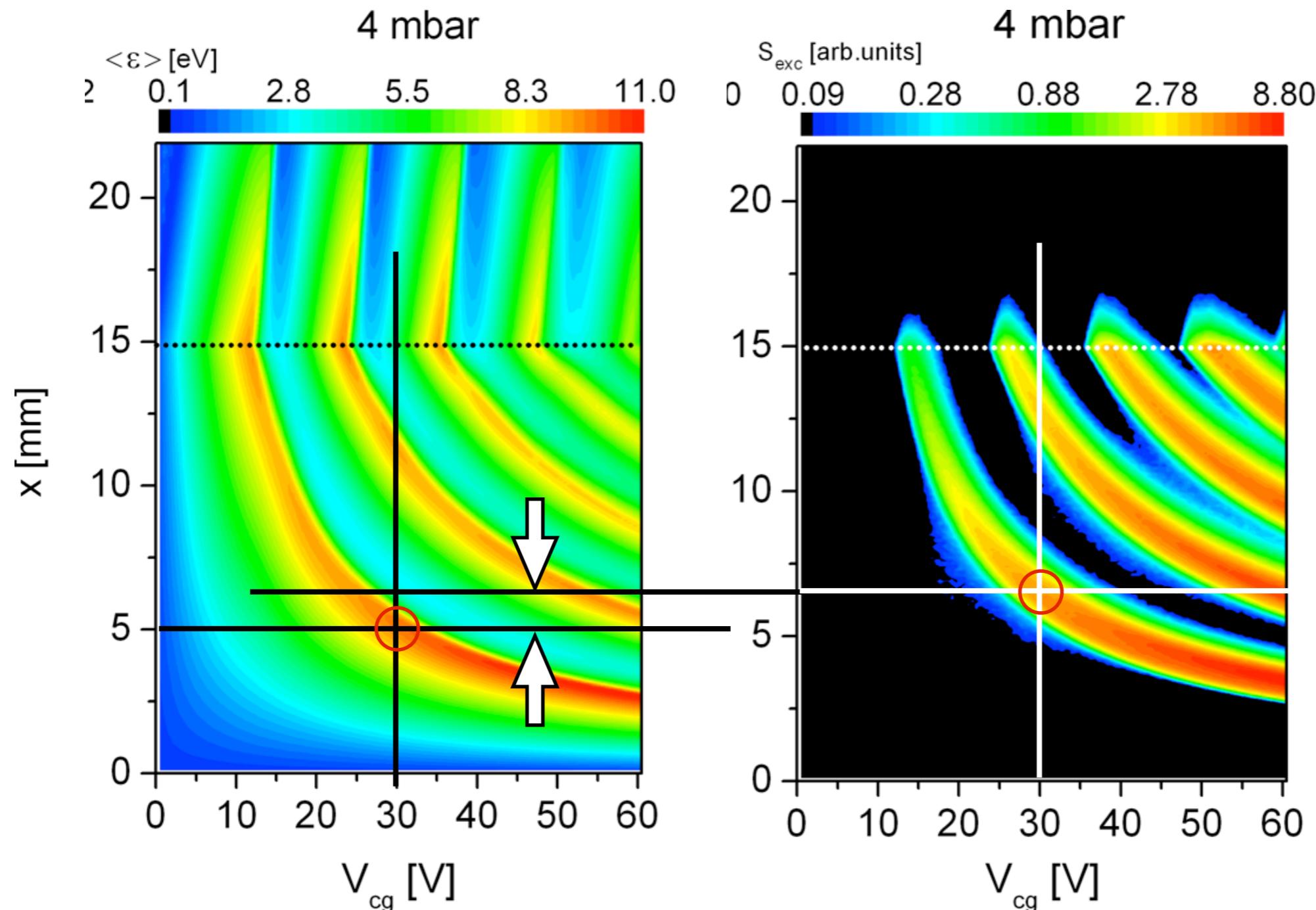


The spatial distribution of the excitation events becomes less localized with decreasing pressure.

Spatial distribution of the ionization rate



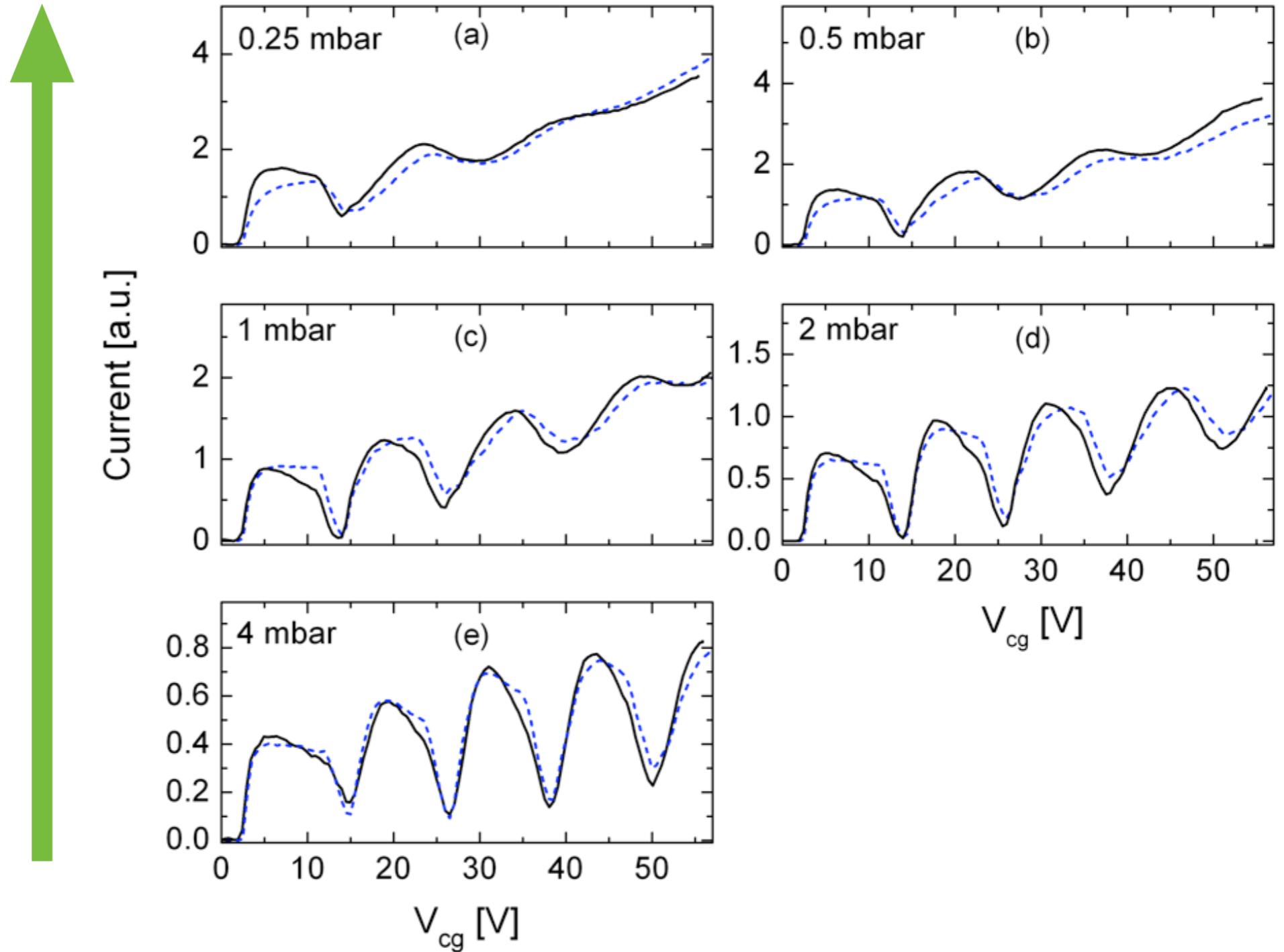
Distribution of mean energy vs. excitation rate



The excitation rate “lags behind” the changes of the mean energy.
A kinetic effect.

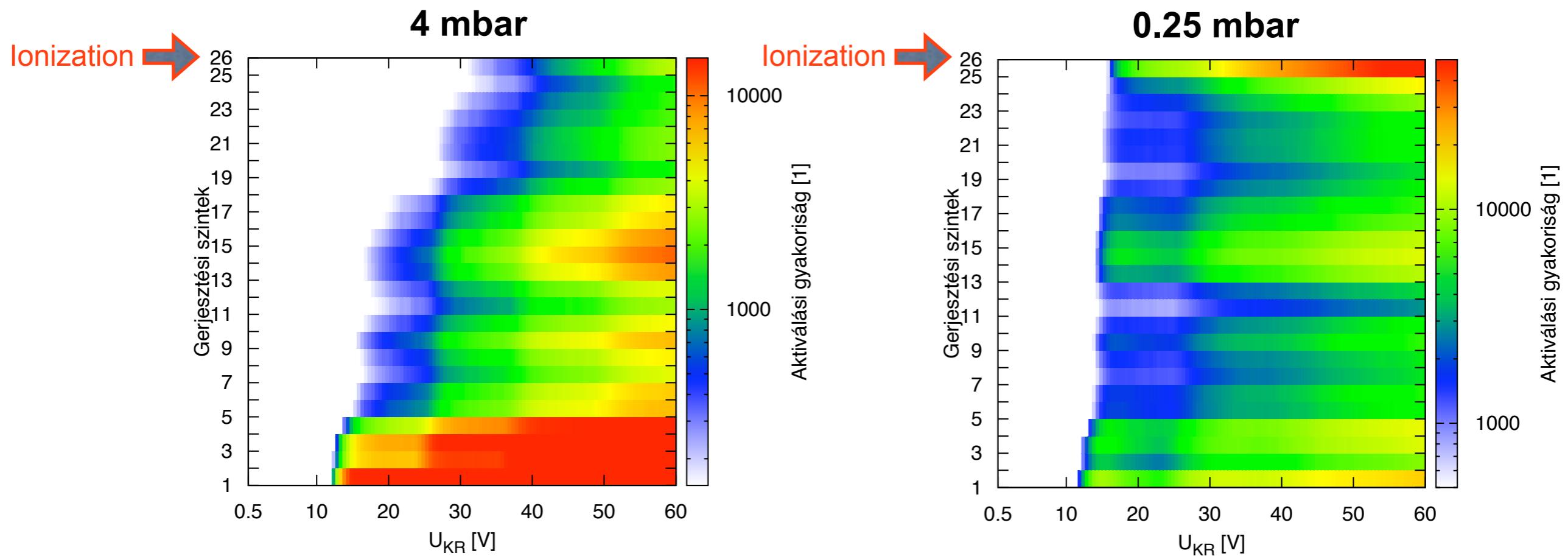
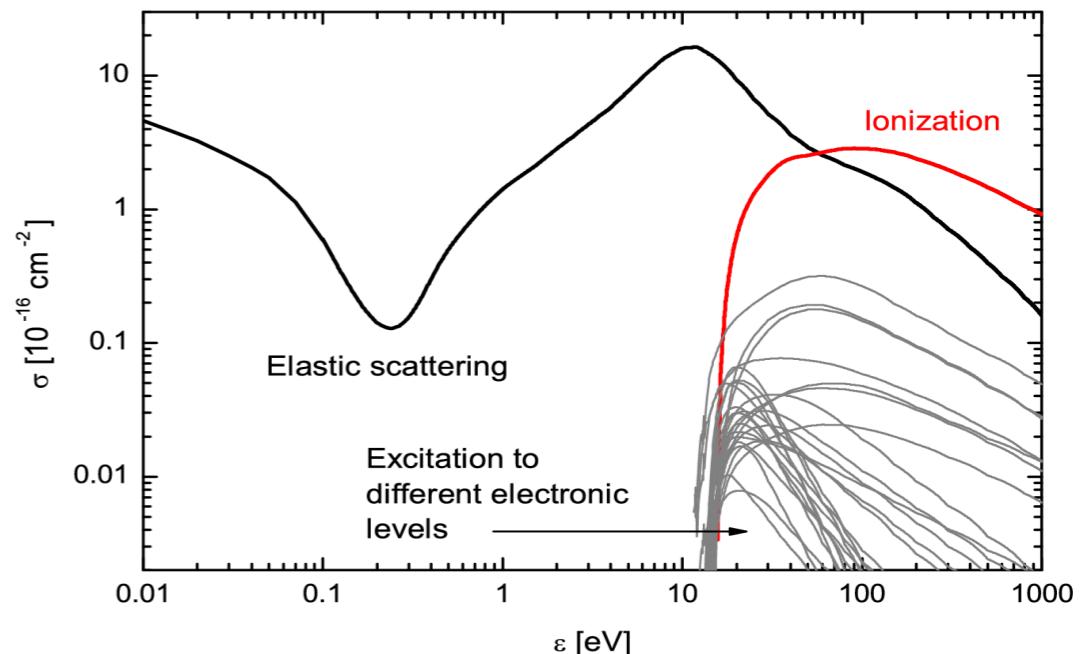
Smearing of the FH current-voltage characteristics

The characteristic periodicity of the anode current disappears with decreasing pressure



Smearing of the FH current-voltage characteristics

- ▶ At low E/n values excitation occurs to a few, lower-lying level of the Ar atom
- ▶ At high E/n values several energy level is populated
- ▶ The ionization events further “mix” the energy distribution
- ▶ Ionization is appreciable at low pressure



Summary

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- ▶ Franck-Hertz experiment: published: 1914, Nobel prize: 1925
- ▶ It is still interesting!
 - ▶ Model and simulations based on kinetic theory
 - ▶ Modern experiment + kinetic description → detailed information about the electron kinetics
[Phys. Rev. E 85, 056409 (2012)]

Thank you for your attention