Muons, Inc.

Overview of MCP Simulation Work

LAPD Project Microchannel Plate Godparent Review

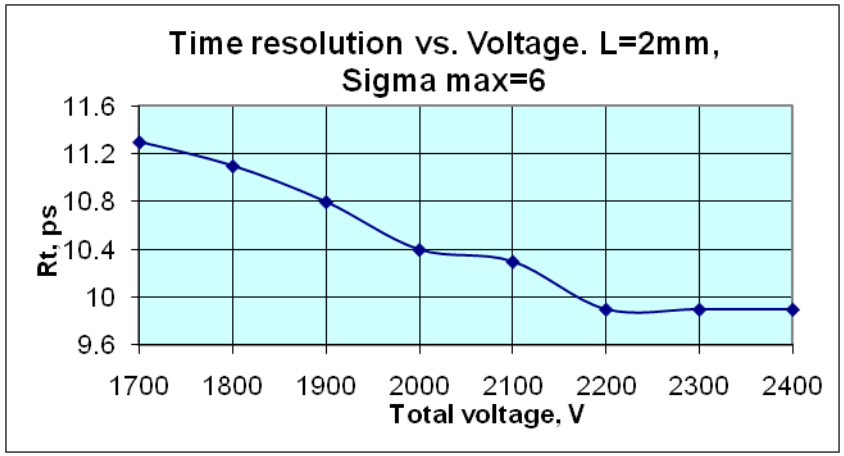
Valentin Ivanov, Zeke Insepov, S.Antipov

25 Mar. 2010

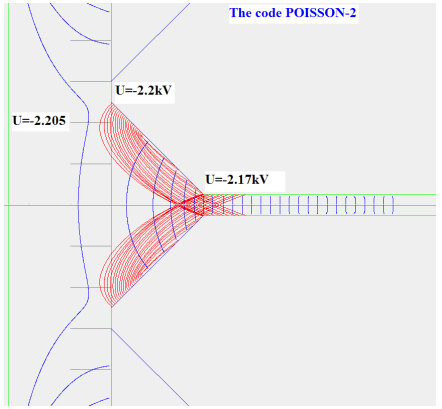
Outline

- Accomplished works to date;
- Current status of the models, computer codes, characterization works and numerical simulations;
- Brief review of future simulation work;
- Problems and challenges we face now.

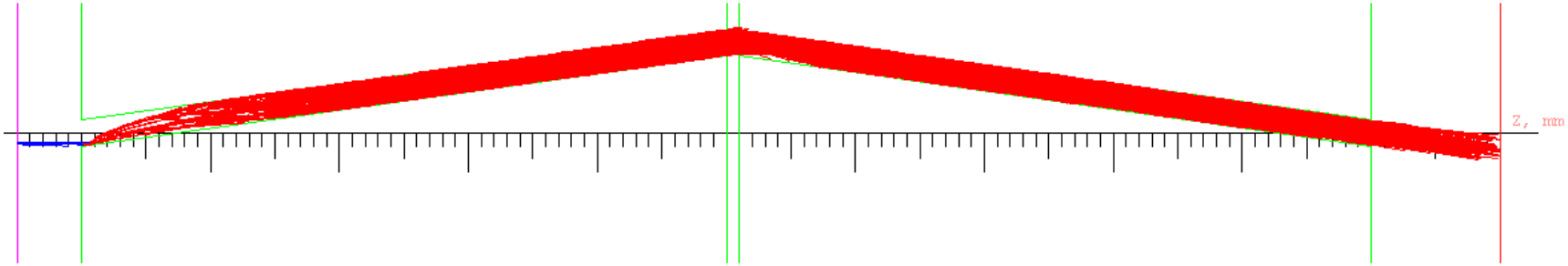
Accomplished works. Software



Time resolution algorithms have been added to the earlier developed code MCPS

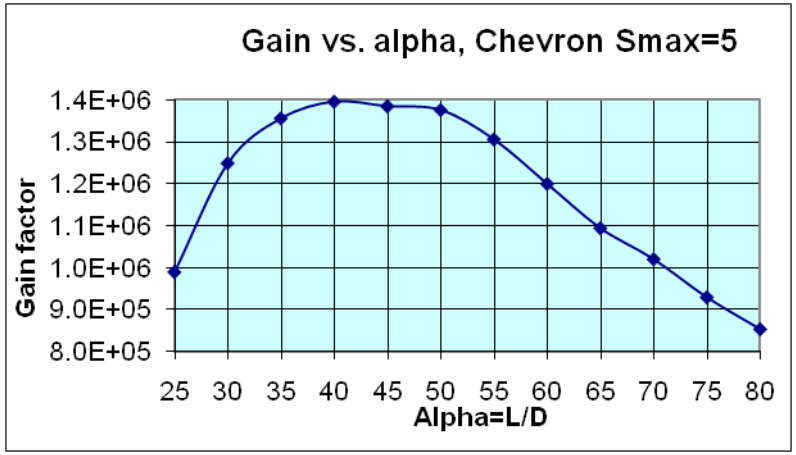


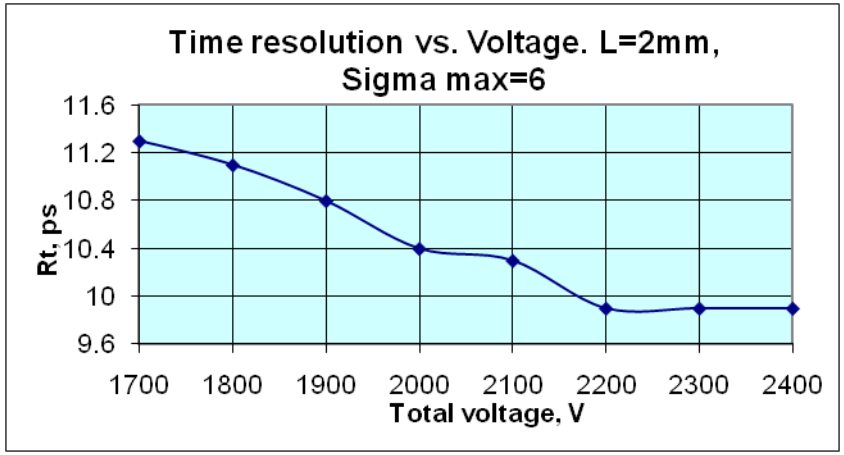
The secondary emission models have been added to the code "POISSON-2" to simulate the funnel type MCP



New 3D code Monte Carlo Simulator has been developed to simulate all kinds of MCPs

Accomplished works. Simulations

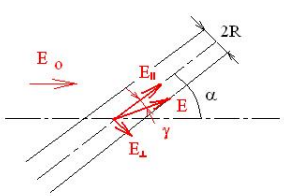


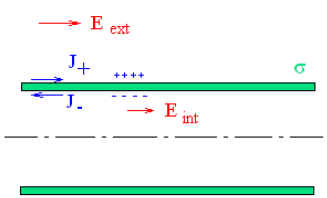


Gain & time resolution depending on geometry parameters, voltage and emission properties have been studies

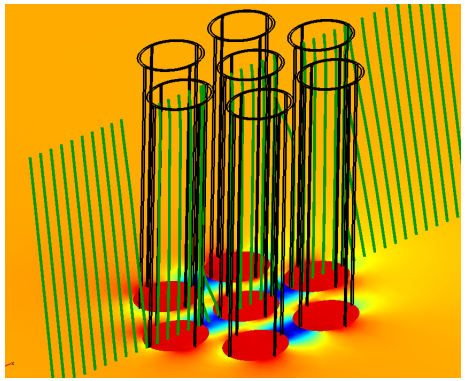
$$\varphi(\rho,\theta) = \begin{cases} -\frac{2\varepsilon_1}{\varepsilon_1+\varepsilon_2} E\rho\cos\theta, & \rho < R, \\ -Ex - \frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1+\varepsilon_2}\frac{R^2}{\rho}\cos\theta, & \rho > R. \end{cases}$$

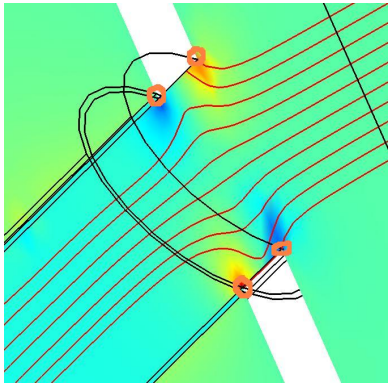
$$E(\rho,\theta) = \begin{cases} \frac{2\varepsilon_1}{\varepsilon_1+\varepsilon_2} E\cos\theta, & \rho < R, \\ E + \frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1+\varepsilon_2}\frac{R^2}{\rho^2}\cos\theta, & \rho > R. \end{cases}$$





Analytical model for the E-field in cylindrical pore with resistive layer





Numerical simulation of the fringe field with COMSOL software

Accomplished works. Simulations-2

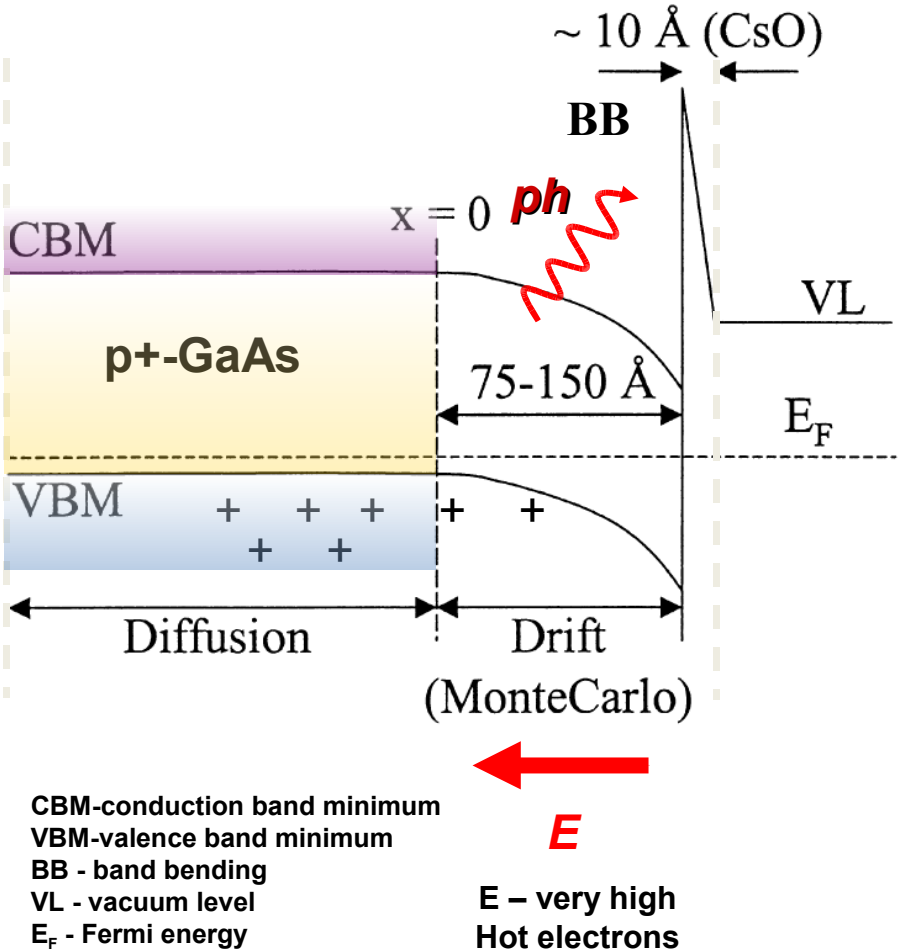
Theory/simulation tasks for photo-emitter developments

Z. Insepov, V. Ivanov
K. Attenkofer, B. Adams (or TBN post-doc)

Photocathode development and simulation

- **Theory/Simulation tasks**
- **NEA photocathodes**
- **Pillar simulation**
- **Angular dependence of Gain, TTS**
- **Time Drift Simulation**
- **Aging effect can be studied by MC/MD**

NEA photocathodes



CBM-conduction band minimum
VBM-valence band minimum
BB - band bending
VL - vacuum level
E_F - Fermi energy

E – very high
Hot electrons

[G. Vergara et al., Surf. Sci (1999)]

Theory of NEA device.

$$Y_X = \frac{P_X F_X}{1+(1/\alpha L_X)}(1-R),$$

$$Y_\Gamma = (1-R)\frac{P_\Gamma}{1+(1/\alpha L_\Gamma)}\left\{F_\Gamma + \frac{F_X L_\Gamma}{\alpha L_X (L_\Gamma + L_X)(1+(1/\alpha L_X))}\right\}.$$

$$L = \sqrt{D\tau} = \sqrt{\mu\tau(kT/e)},$$

$F_{X,\Gamma}$ - distribution of PE in X,Γ vallies (Ab-initio),

$P_{X,\Gamma}$ - probability to escape into vacuum (MC),

τ - recombination lifetime of Γ - electrons (MC),

R - reflection coefficient (MC).

[James, Mall (1969)]

e-LO-phonon scattering – main mechanism of energy relaxation in GaAs
e-plasmon collision – relaxation of energy in the bulk p^+-GaAs volume
e-charged impurity relaxation – in depleted region
e-h pair generation – in depleted region

Theory, simulation vs exp for NEA-GaAs

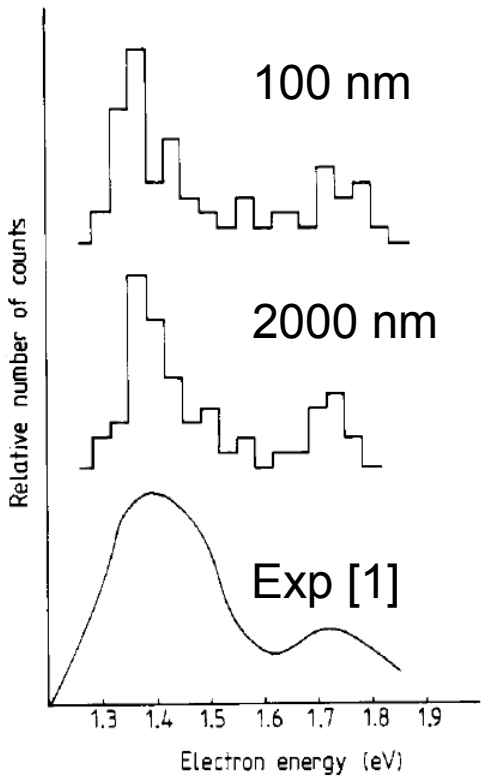
- James, Moll, Phys.Rev. (1969) – model and **two peak energy distribution**
- Escher, Schade, JAP (1973) – theory : **one peak**
- Phillips, Hughes, Sibbett J. Phys. (1984) – **one peak**

Yang, Xu J. Phys. (1990) – Monte Carlo – one & two peaks

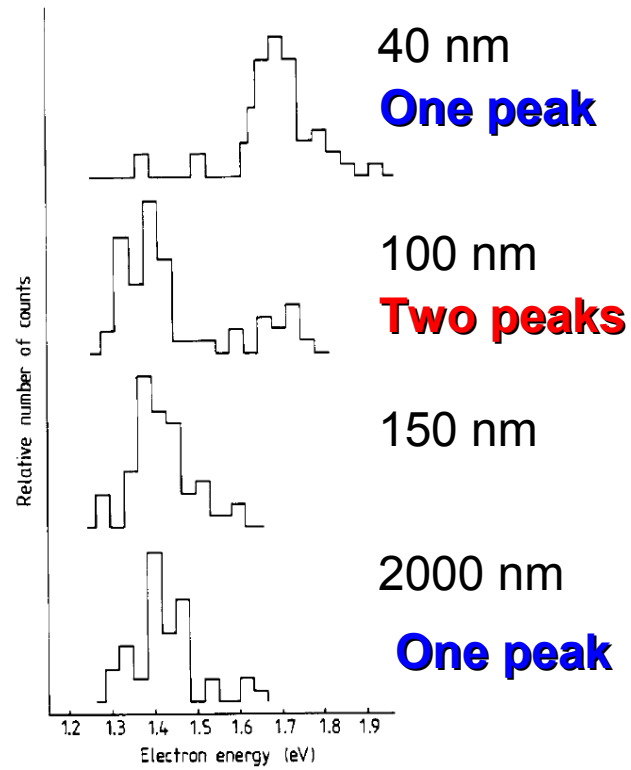
$N_A = 1\times10^{19}$ cm^{-3}

$h\nu = 2$ ev

Reflection mode

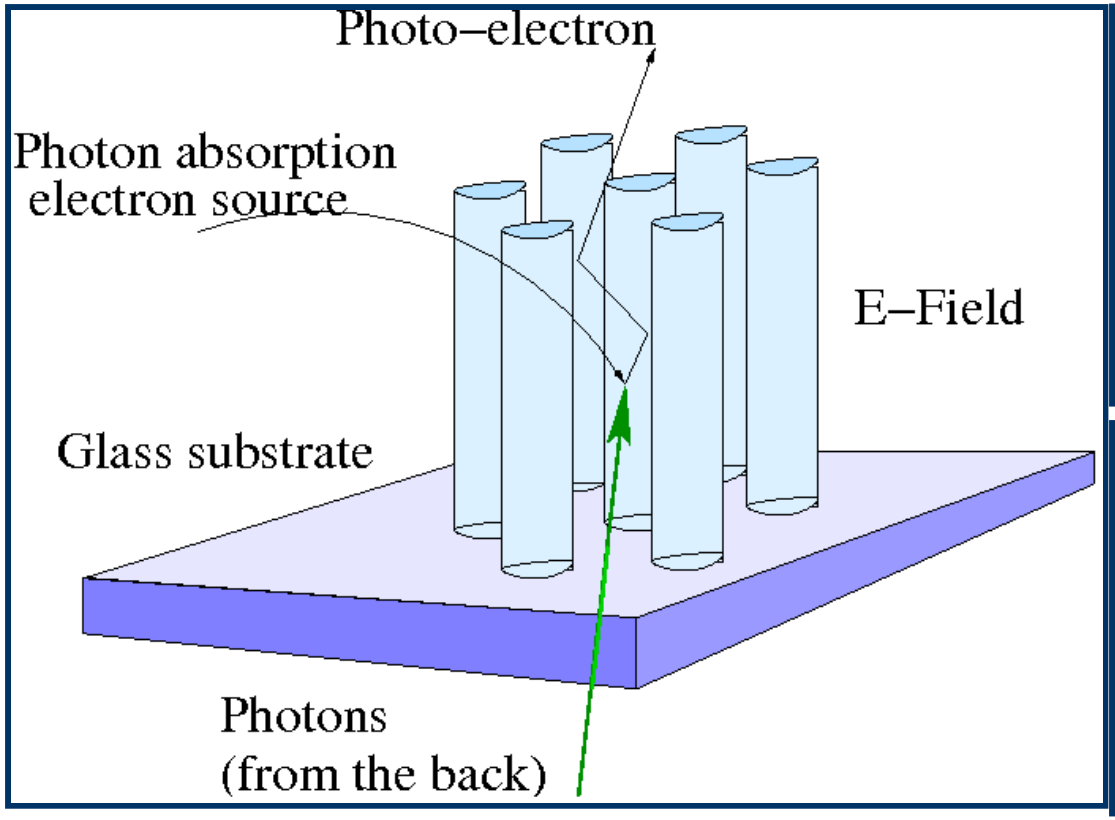


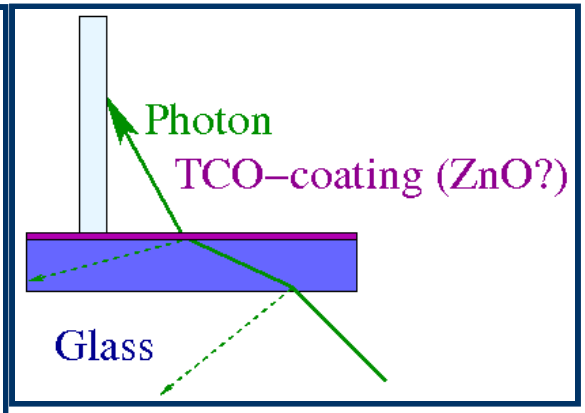
Transmission mode

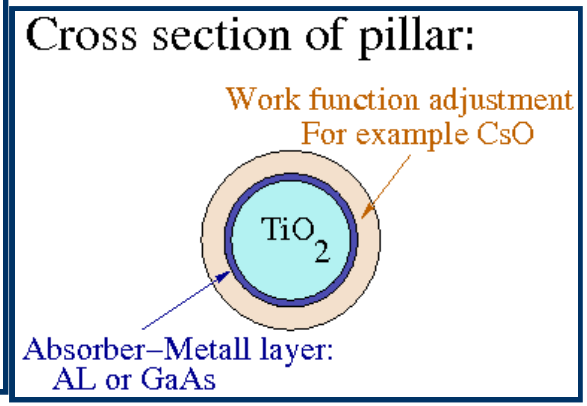


[1] James, Moll (1969)

Pillar structure

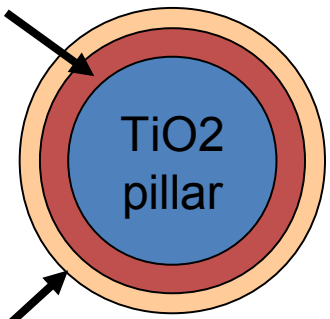


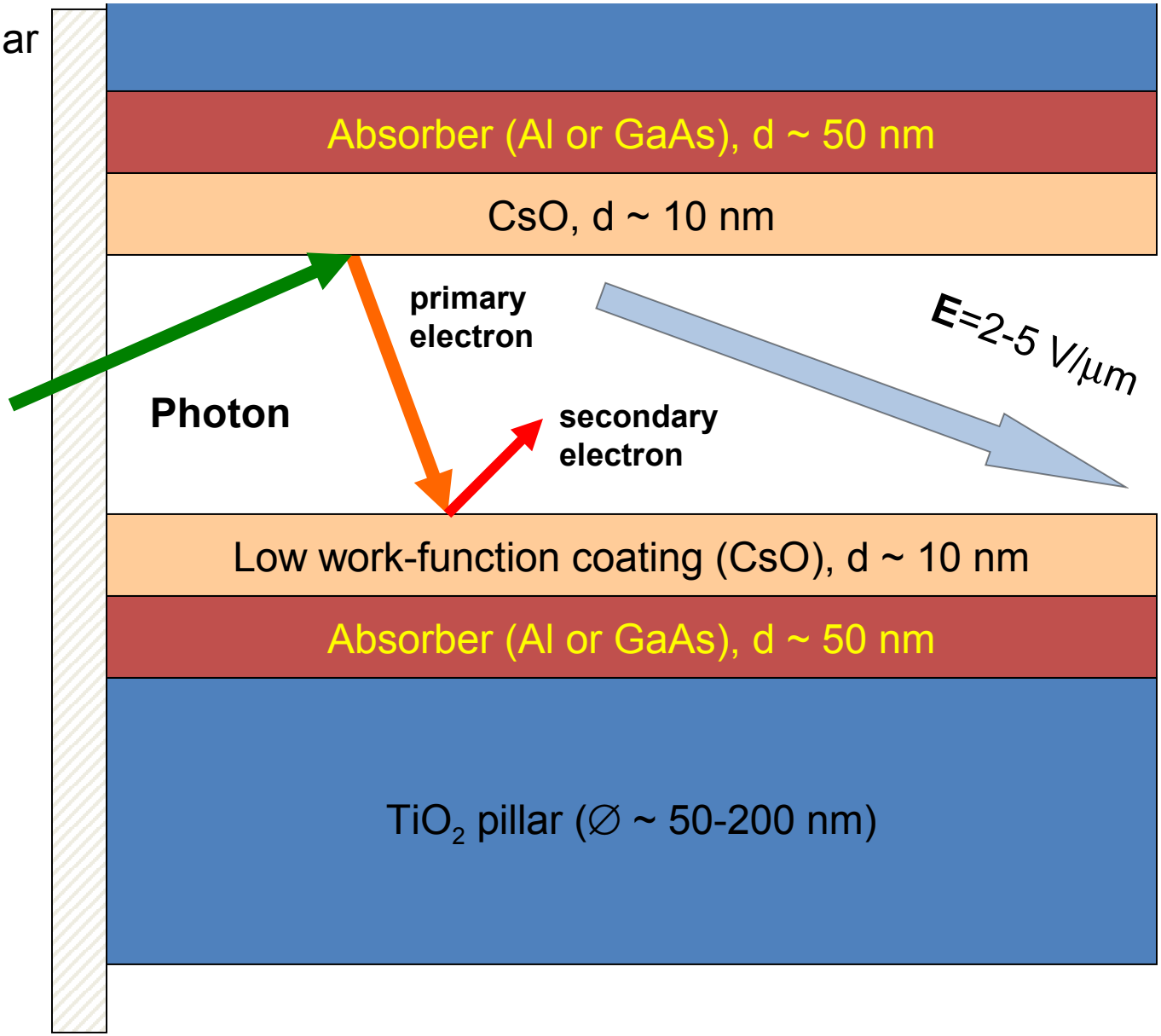




Pillar simulation

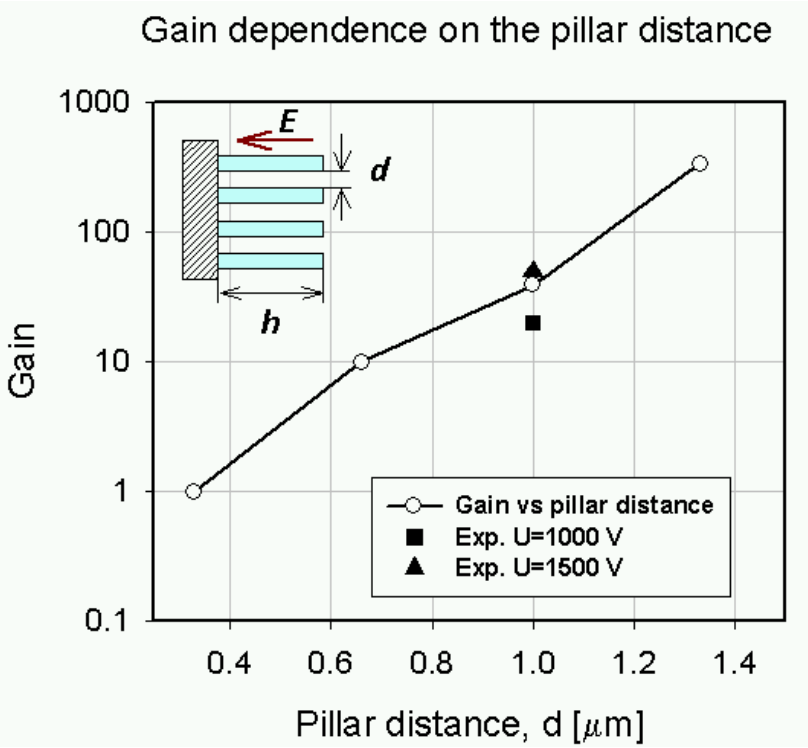
Cross-section of pillar

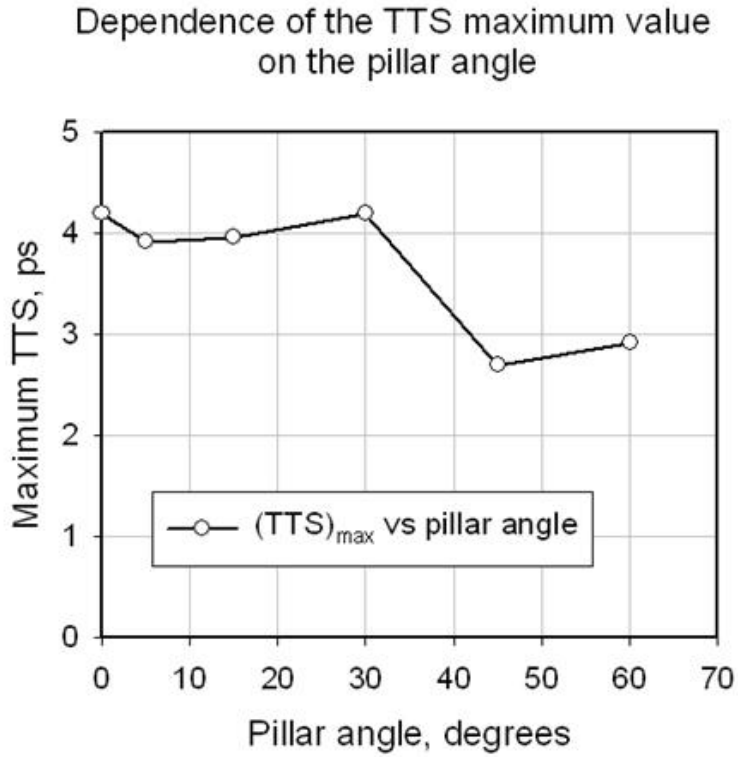




Z.Insepov, V. Ivanov

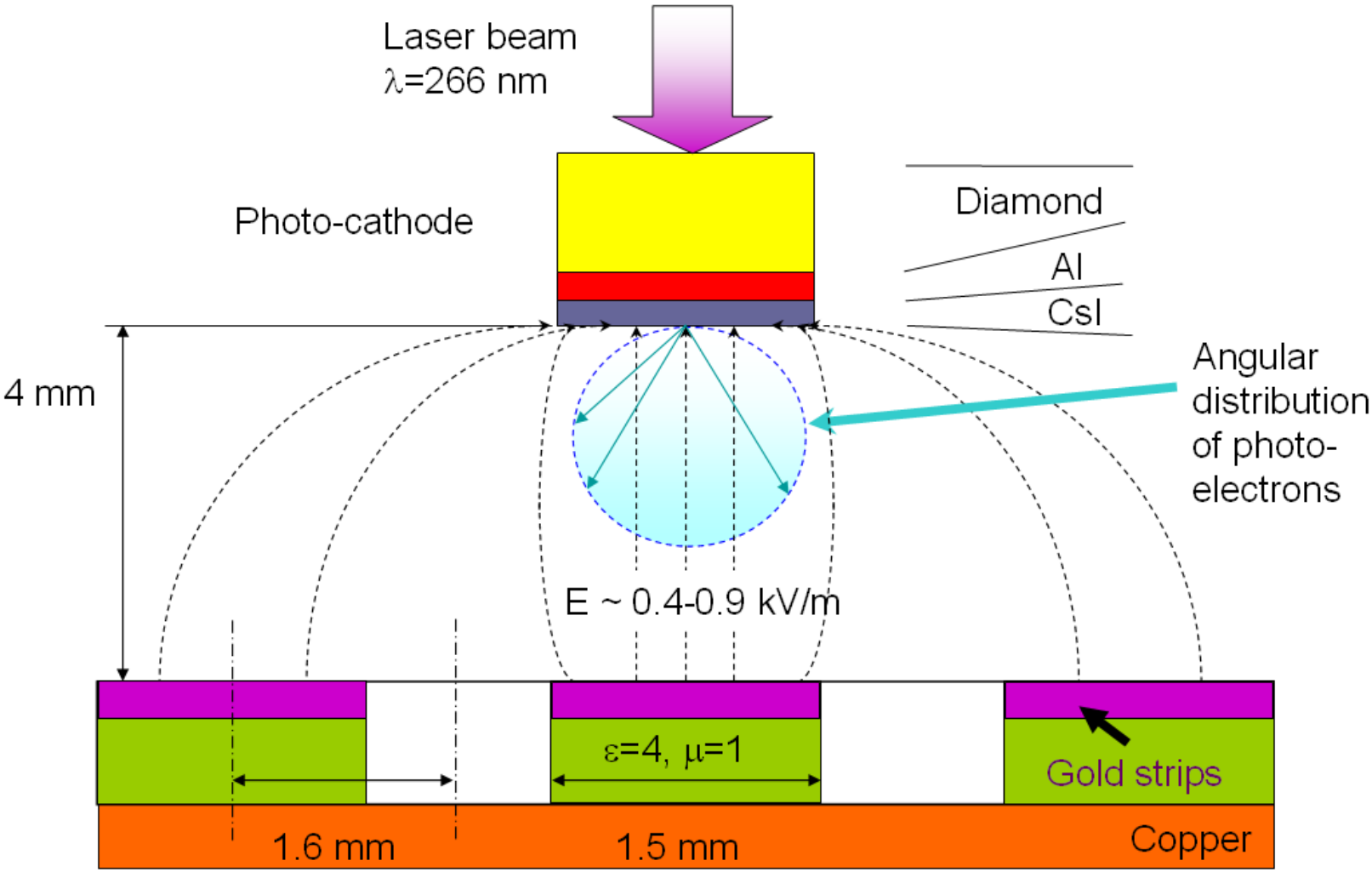
Gain – our simulations vs. experimental data by A.Lyashenko!



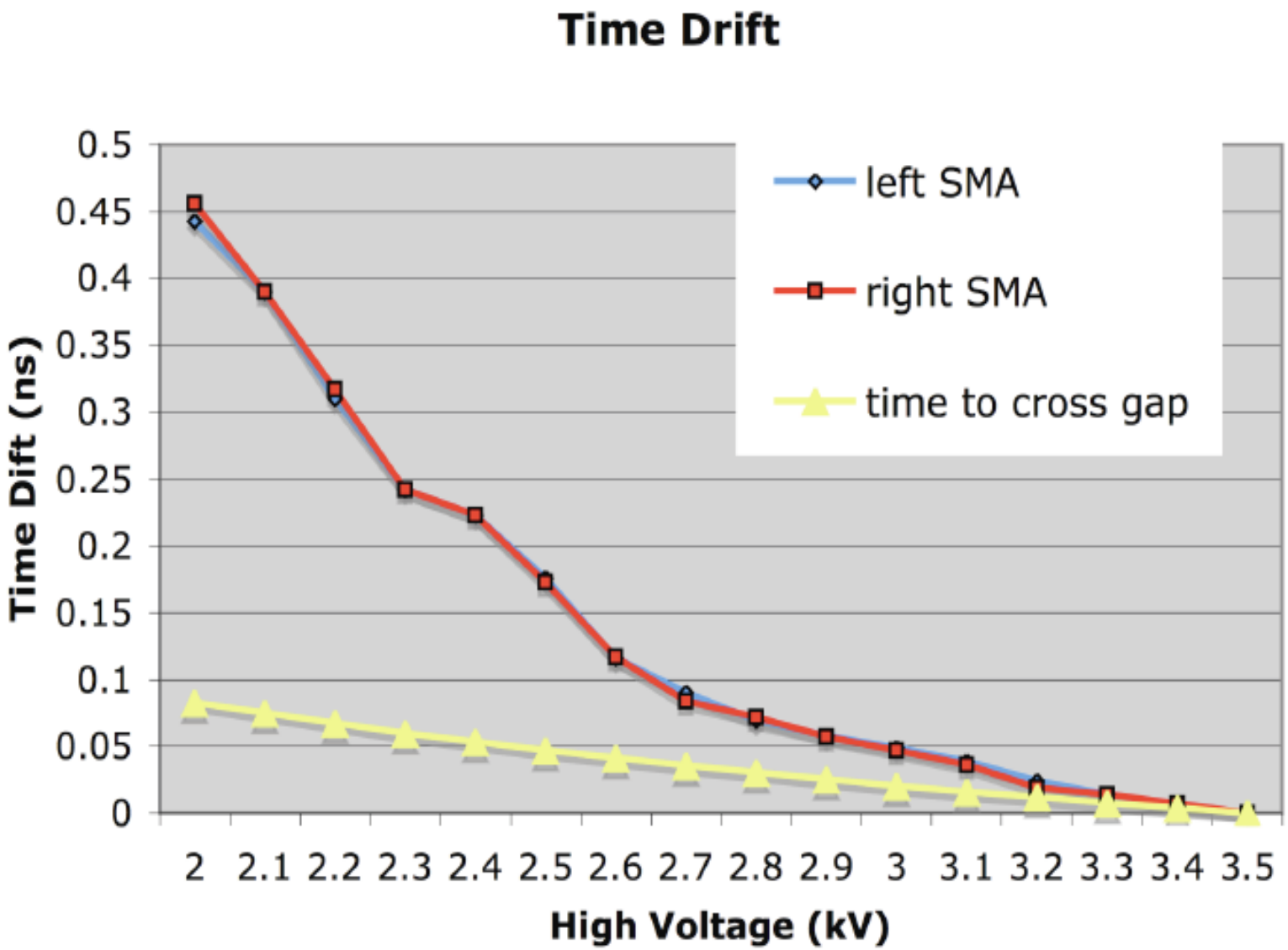


There is a good agreement between numerical and experimental results.
Here U=1000V, D=0.33-1.33um, asp. ratio = 200, initial energy for secondaries ≈ 5eV.

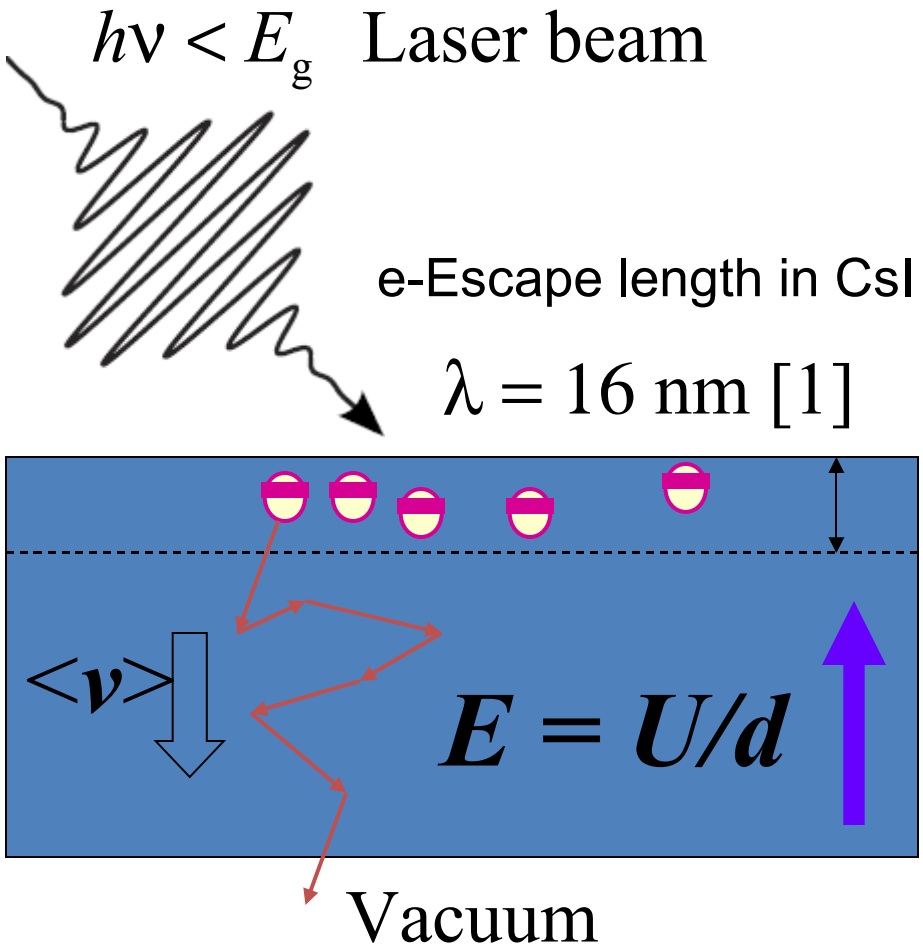
Time Drift Simulation



APS experiments



Drift-diffusion model of electrons



Drift+Diffusion model

Langevin equation

$$\dot{\vec{v}}_i(t) = -\nabla U(\vec{r}_i)/m_e - \gamma \cdot \vec{v}_i(t) + \vec{R}_i/m_e,$$

γ – friction coefficient, $\vec{R}_i$ random force,

$$\langle R(t) \rangle = 0,$$

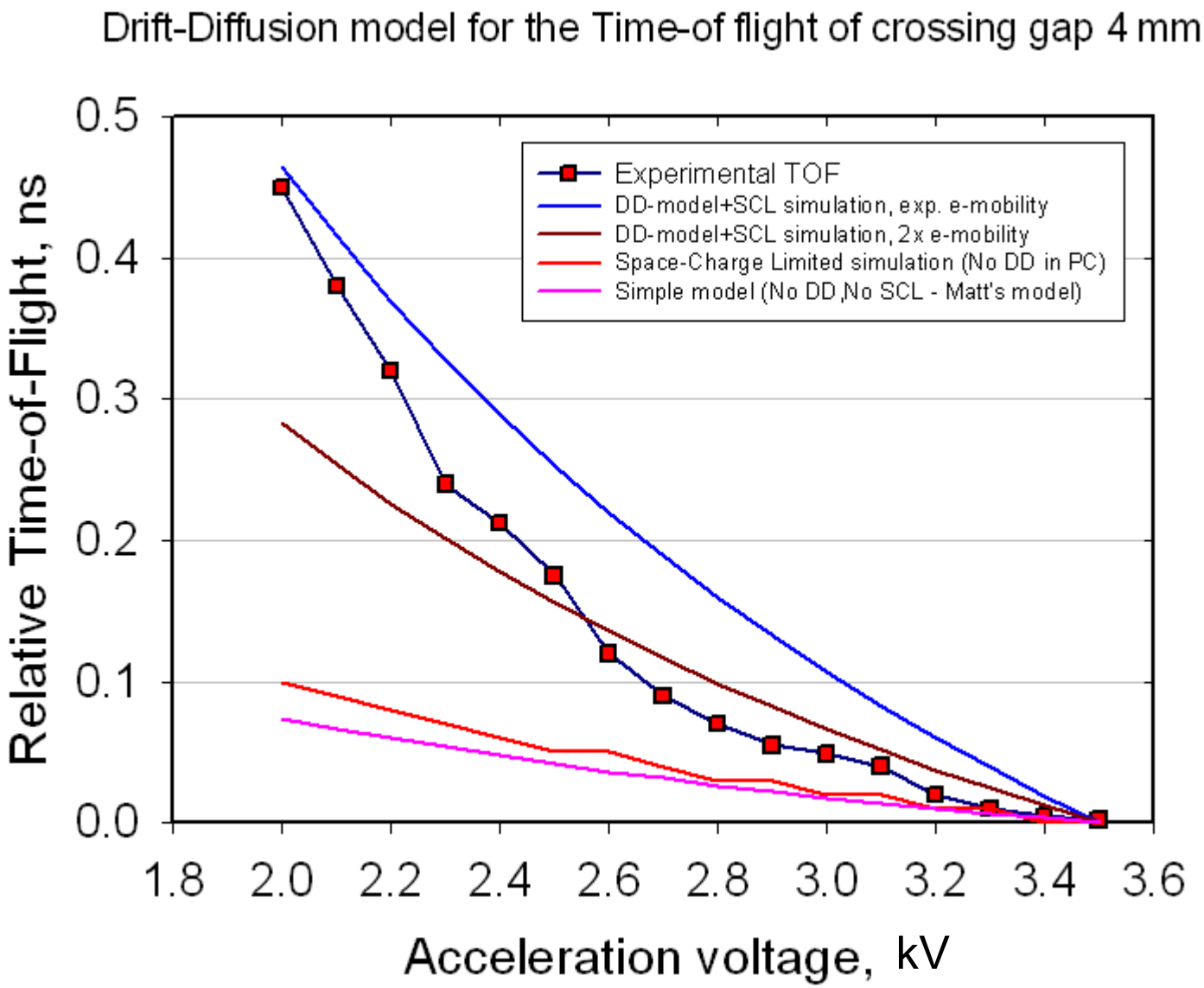
$$\langle R(t)R(t') \rangle = 2\frac{\gamma k_B T}{m_e}\delta(t-t').$$

e – mobility

$$\mu_e = 8\times 10^{-4} m^2/V\cdot s \text{ [2]}$$

[1] Breskin, NIMA (1996)
[2] Aduev, Phys.Stat.Sol. B (1998)

Time to Drift in vacuum



Summary-2

- NEA models will be modified (+L point)
- MC micro-code #1 will be developed for micro- PC modes (reflection + transmission mode)
- MC macro-code #2 will be developed for Gain, TTS
- PC coatings can be studied by MC
- Drift time can be calculated by MC and compared to Matt's experiment
- Ab-initio band structure calculations will be valuable addition to fundamental tasks (Bernhard + TBN) and for simulation parameters
- Dopant profiles, carrier mobility and defect properties will be calculated via a Klaus's software

Accomplished works. Simulations-3

SEE Yields of various materials: Simulation vs Experiment

Z.Insepov, V. Ivanov, S. Jokela

SEE yield calculation

Monte Carlo algorithm

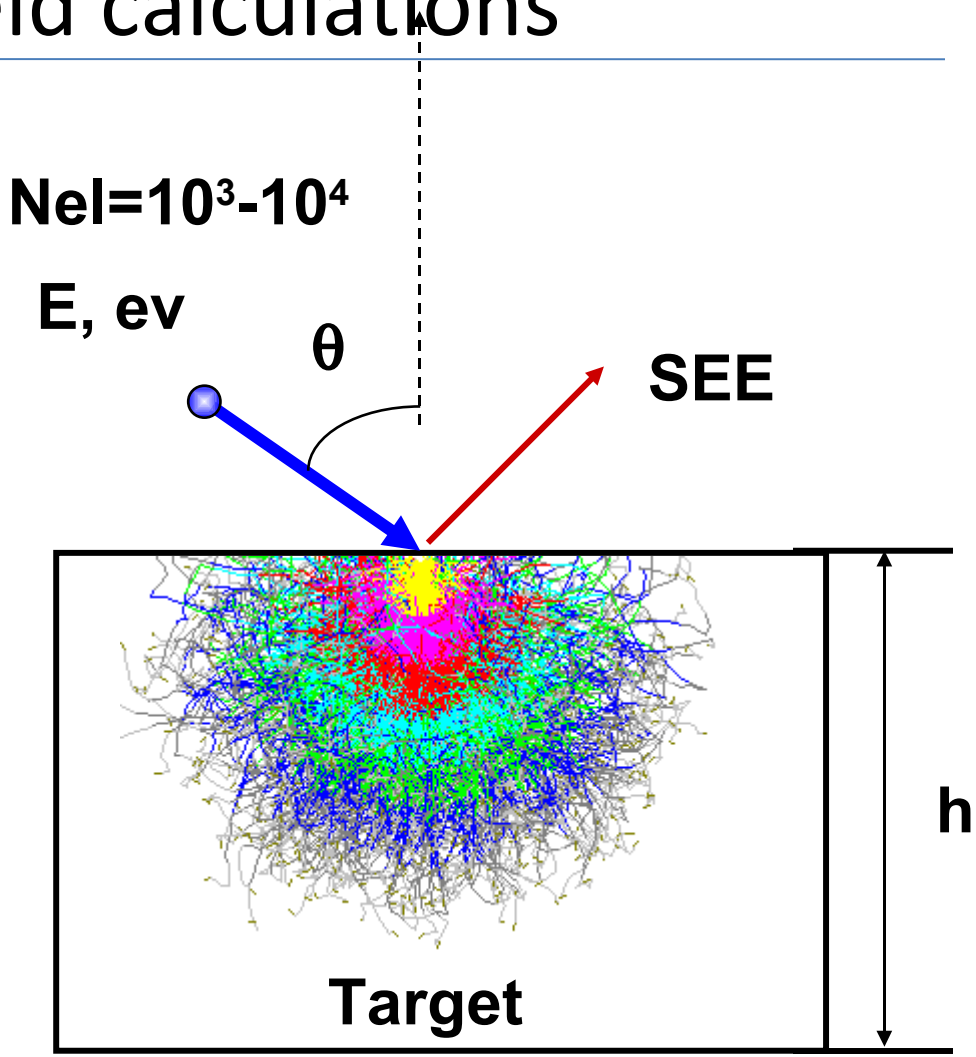
- Initial electrons are created, E=0.1-4 keV, θ =0-89°
- New electron, new trajectory, similar to previous
  - The process continued until the electron $E < E_0$
- 1000 trajectories computed for each sample; (statistics will be improved)
- h=10^2-10^4 Å samples were simulated (100Å - 1 μm)

Experimental data from literature

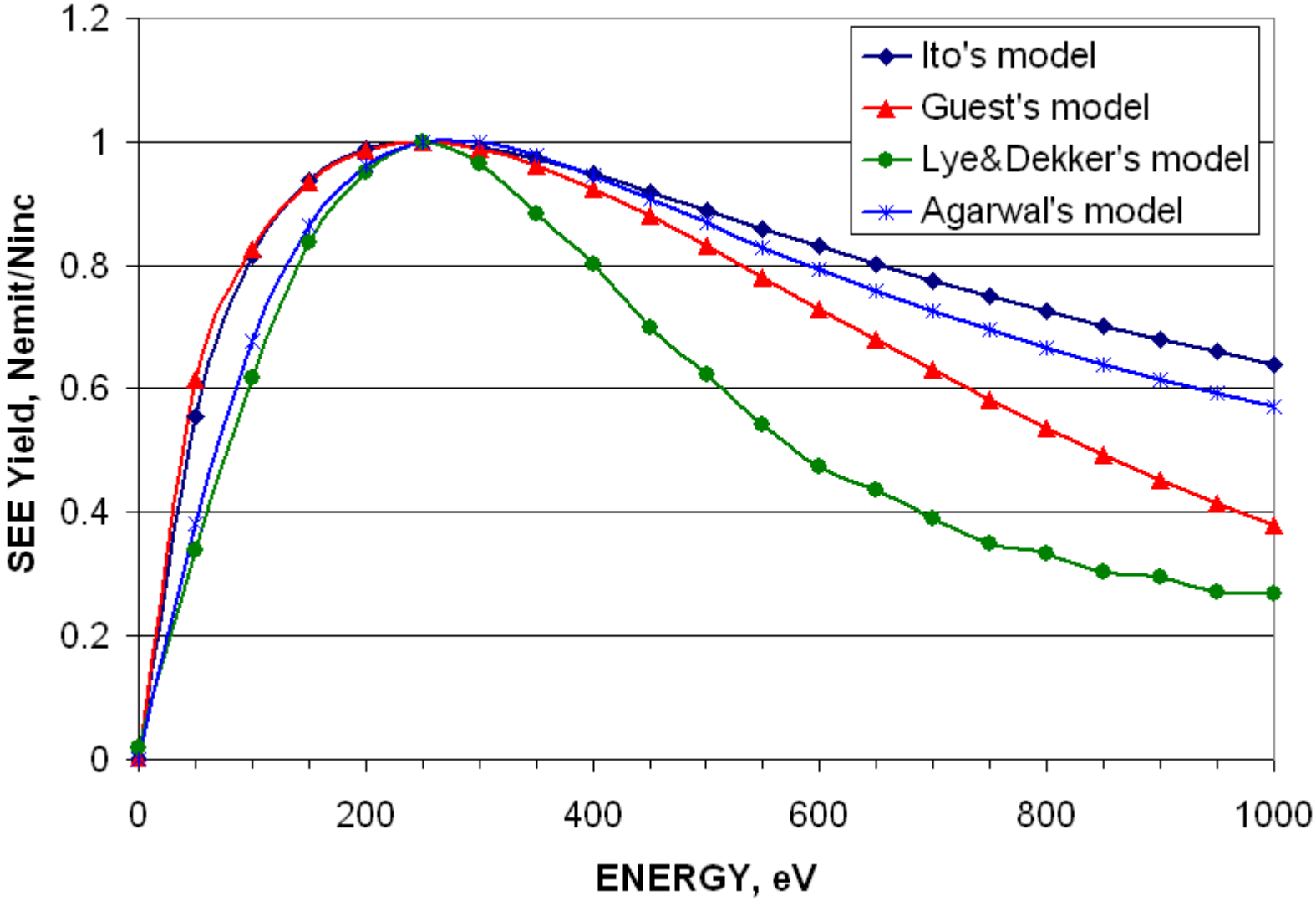
- Experimental SEE yields were compared with our calculations

SEE Yield calculations

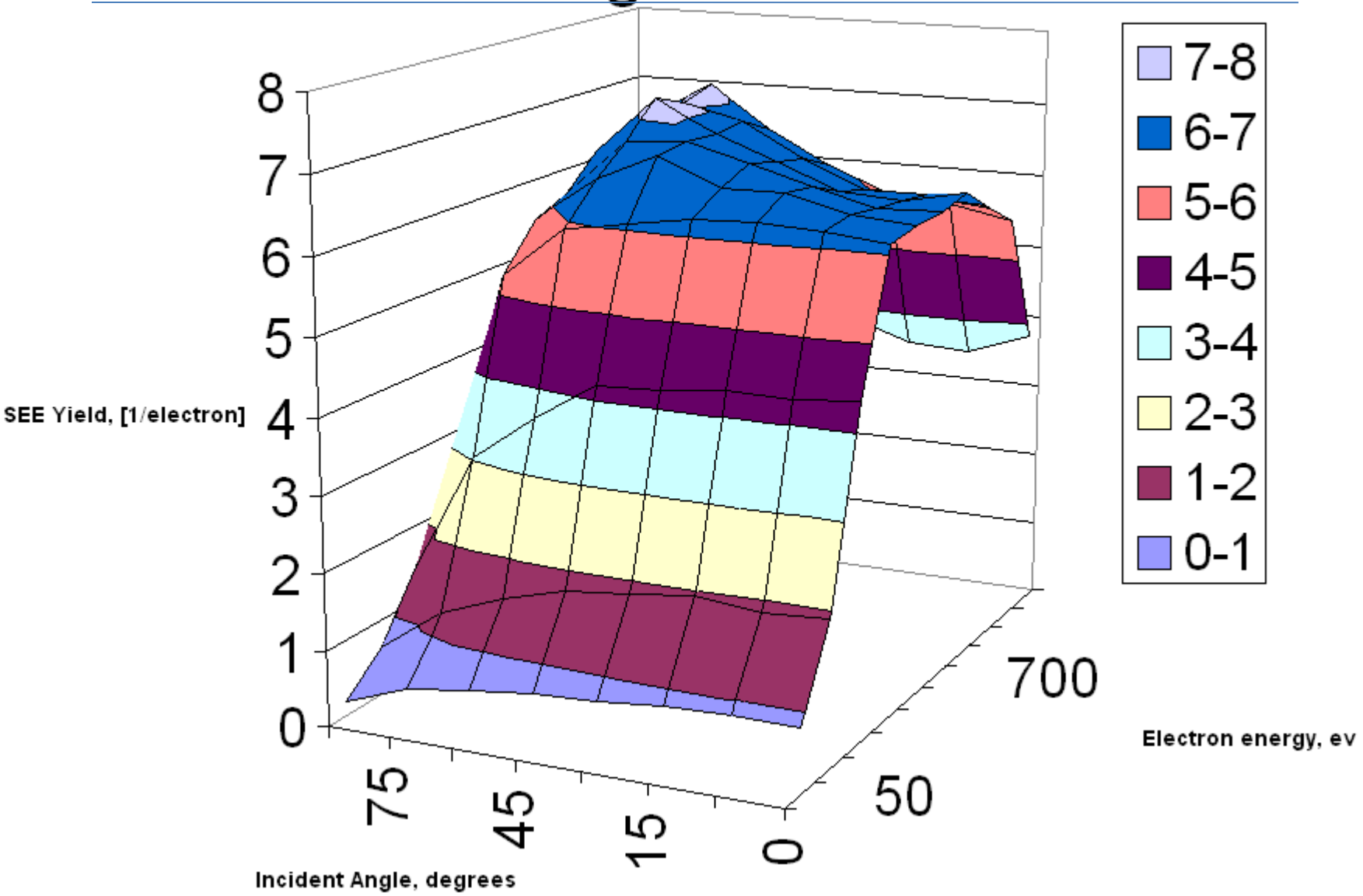
- **MgO**
- **Al2O3**
- **Copper**
- **Gold**
- **Molybdenum**
- **ZnO**



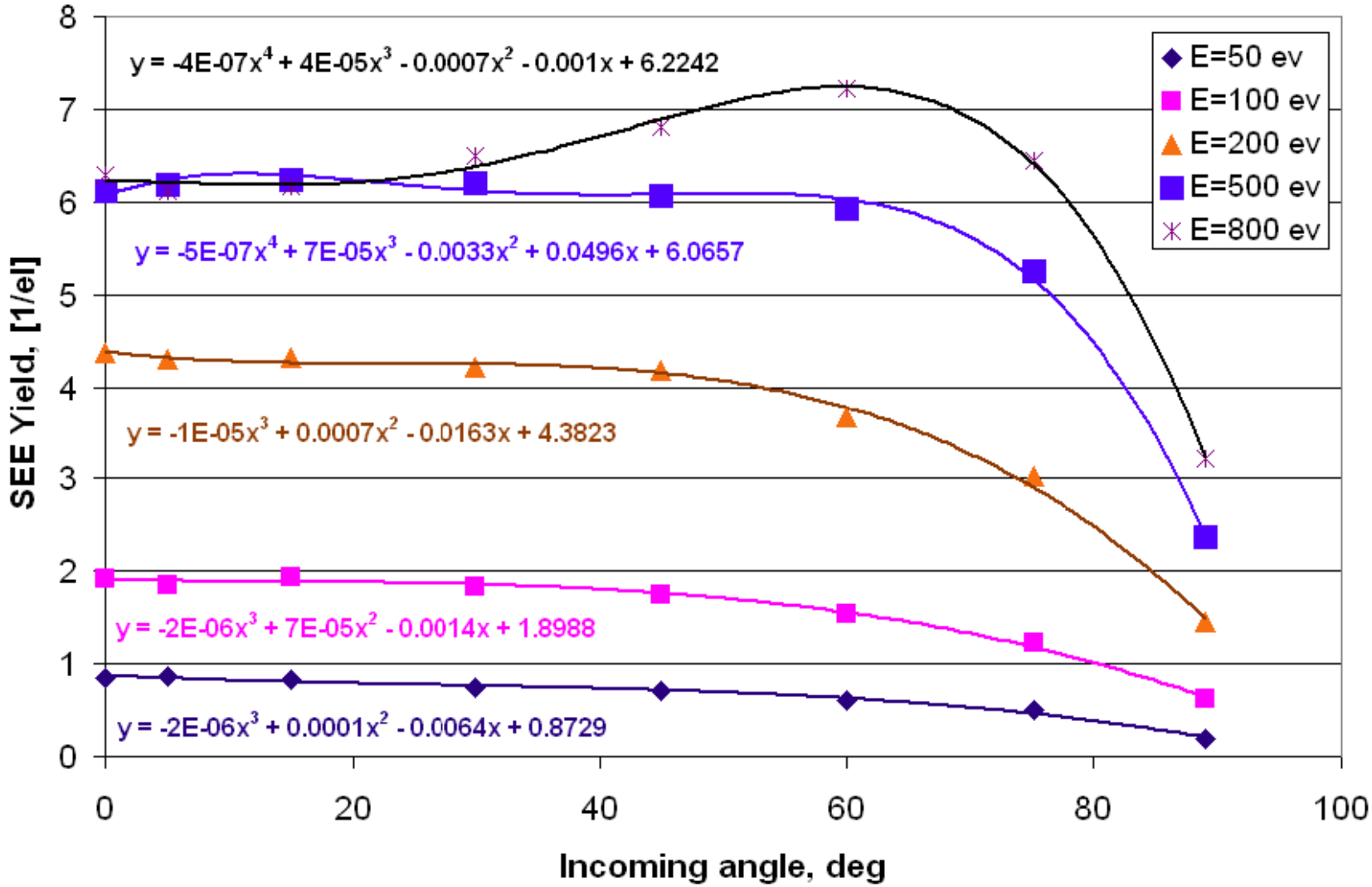
Comparison of SEE- models



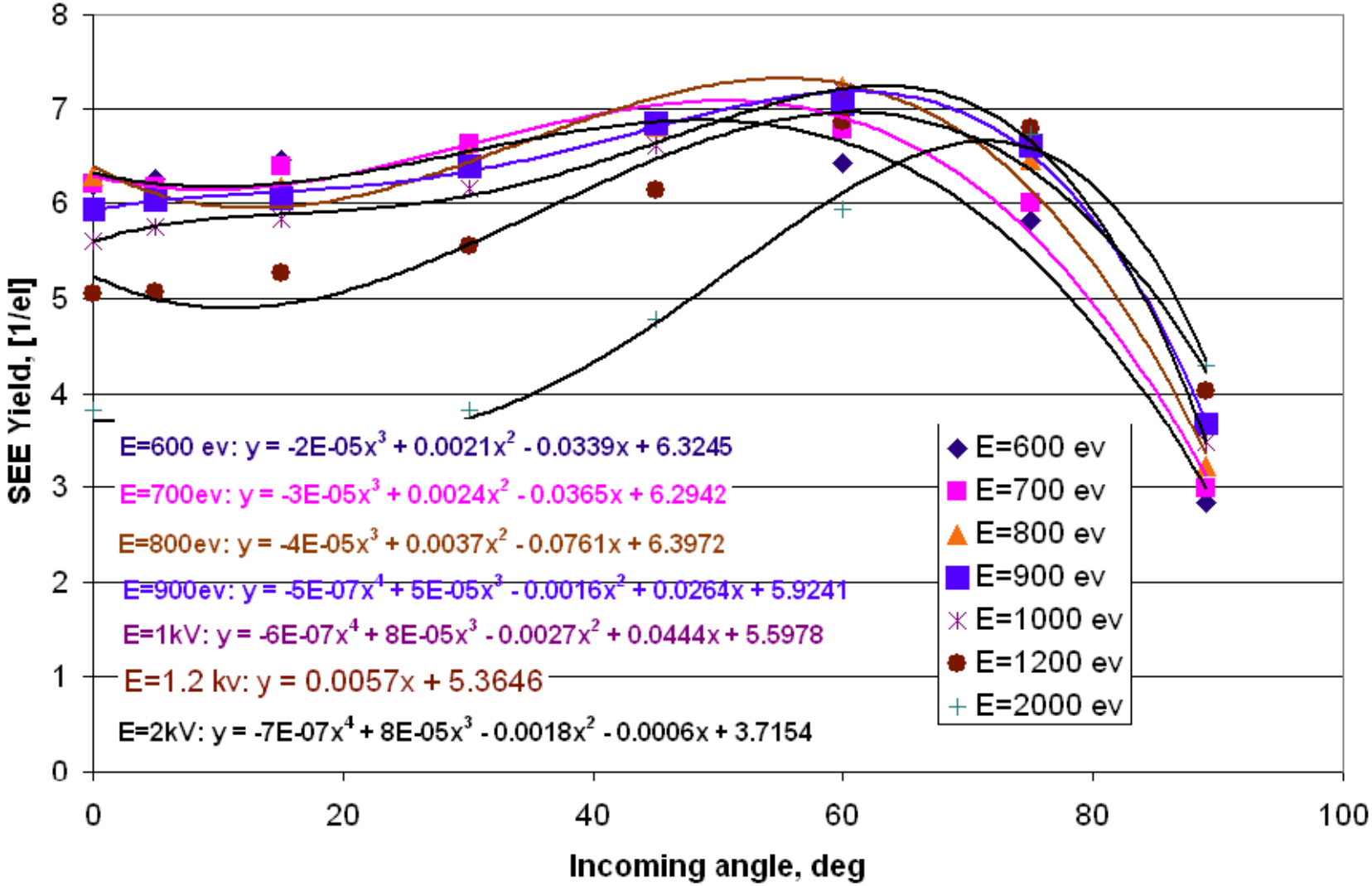
Al2O3 SEE Yield vs E, ev and Angle, degrees



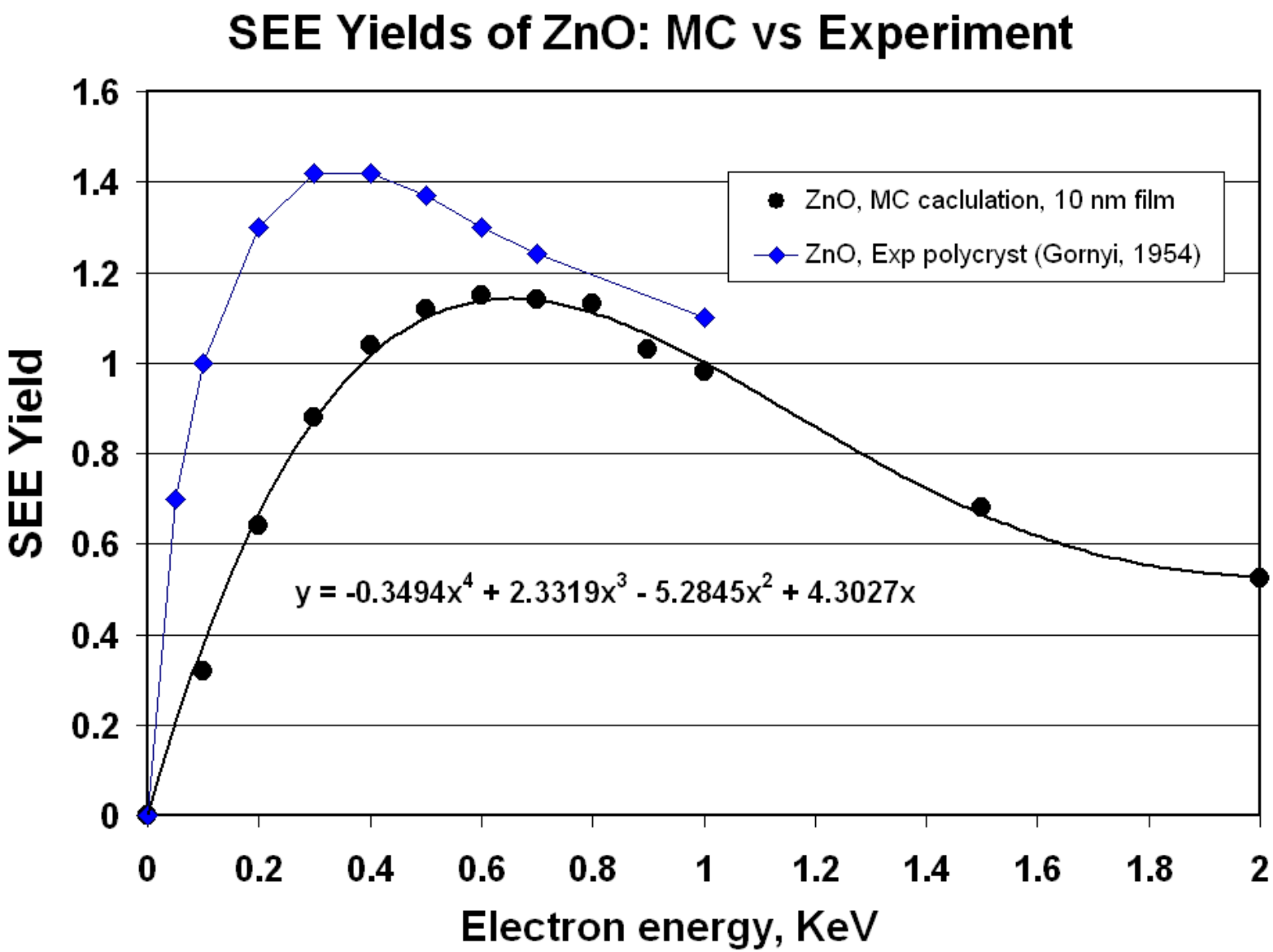
Al2O3 low-energy SEE Yields



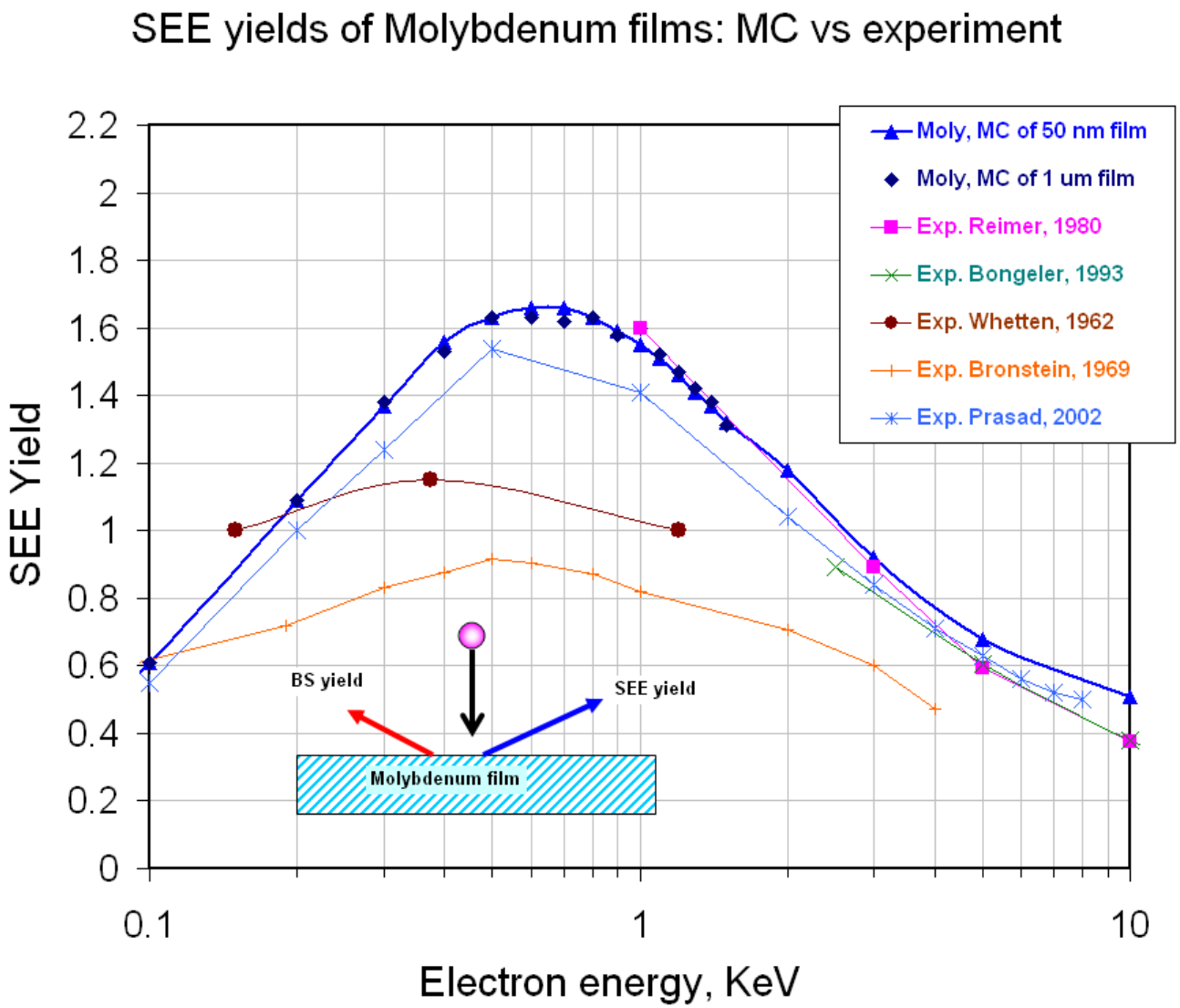
Al2O3 high-energy SEE Yields



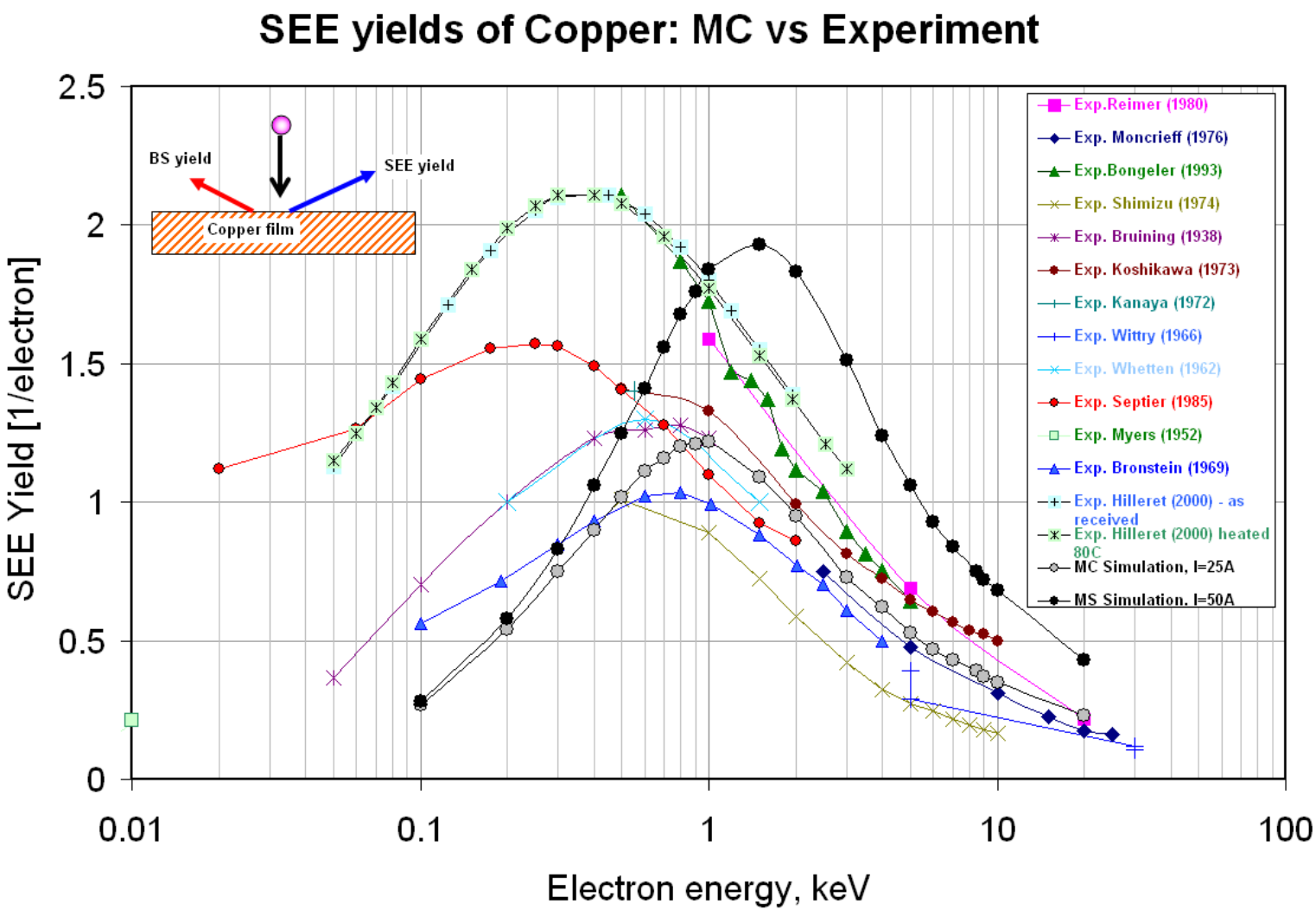
ZnO SEE Yields: MC vs. Experiment



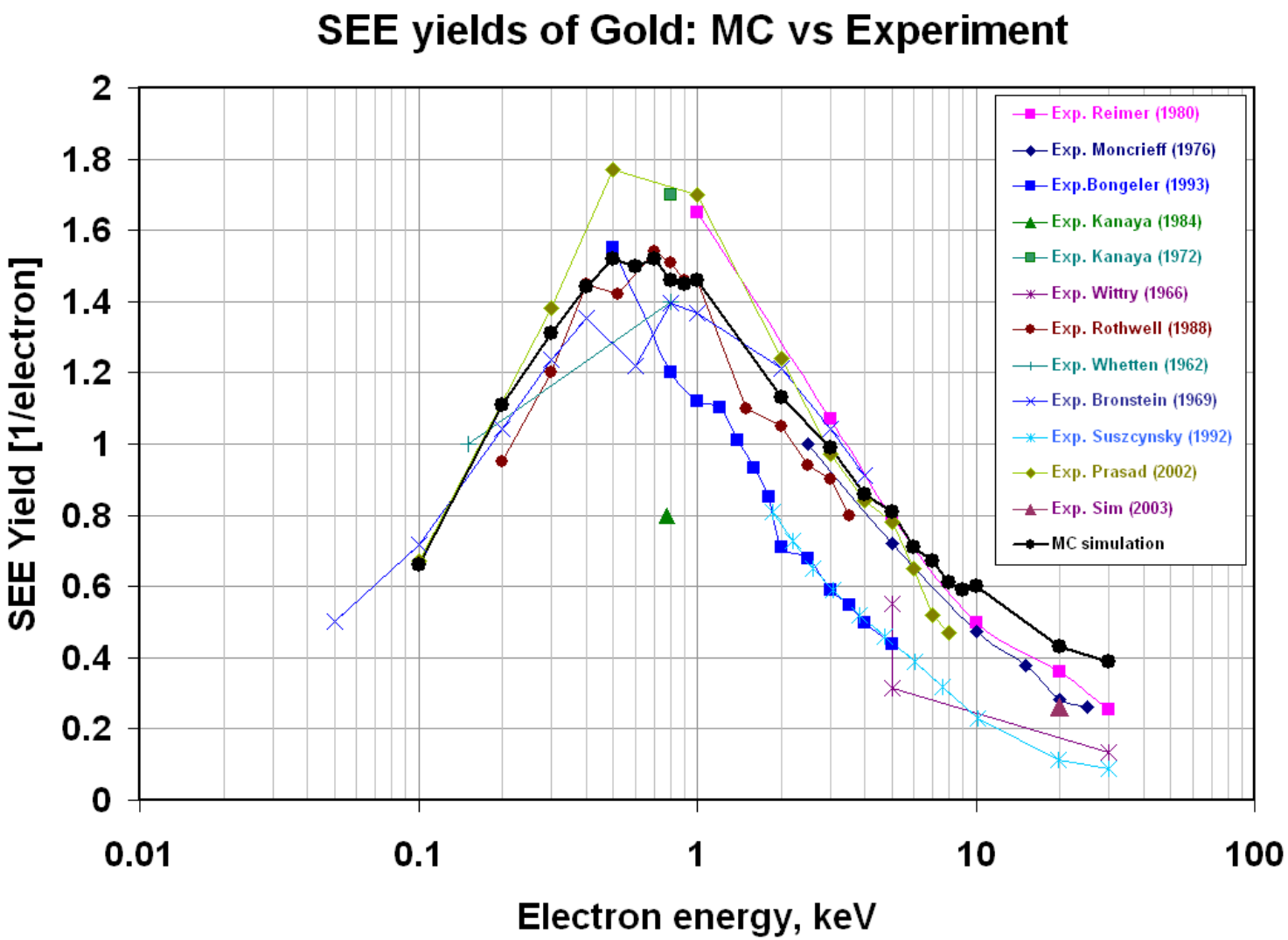
Moly SEE Yields: MC vs. Experiment



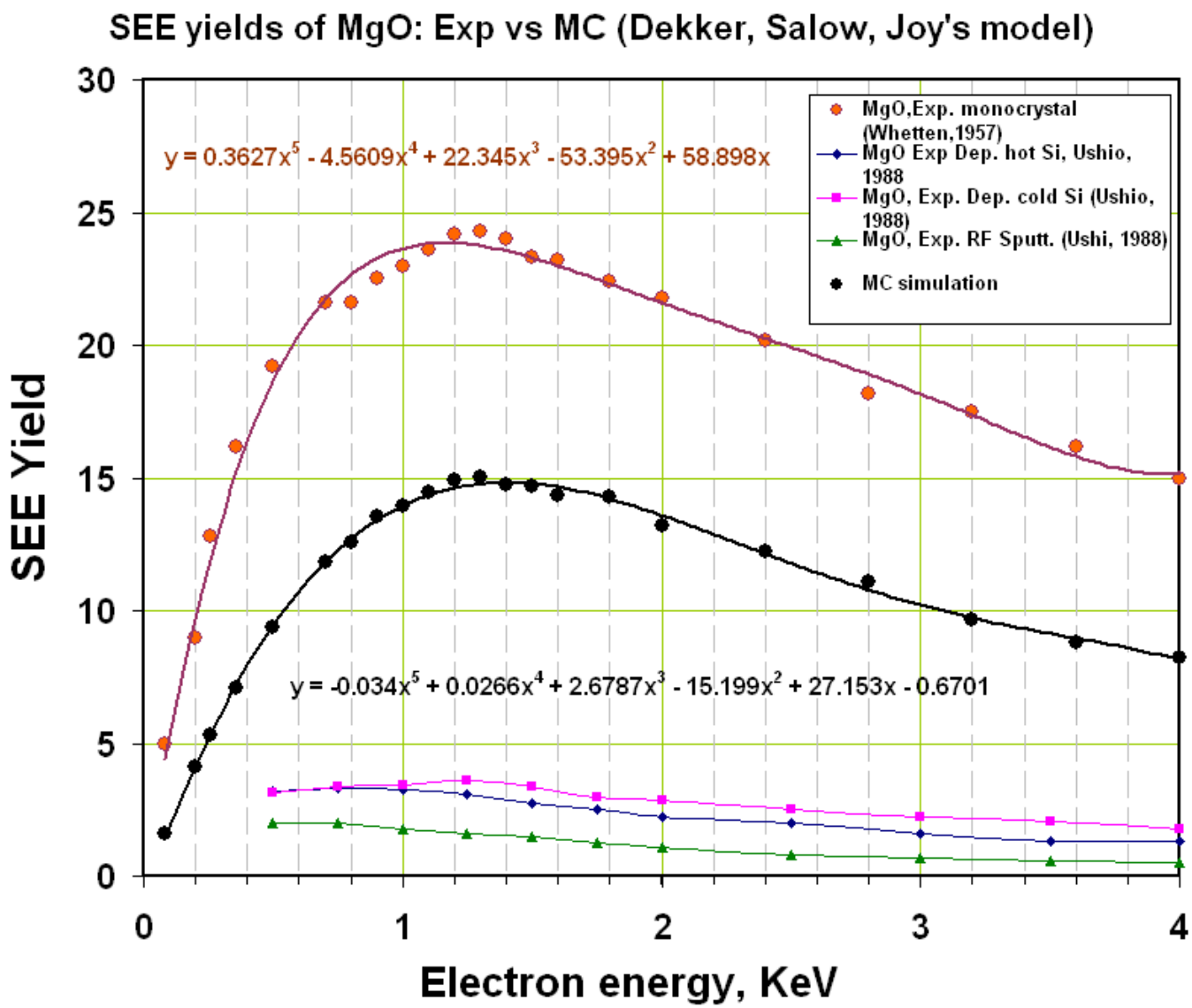
Copper SEE Yields



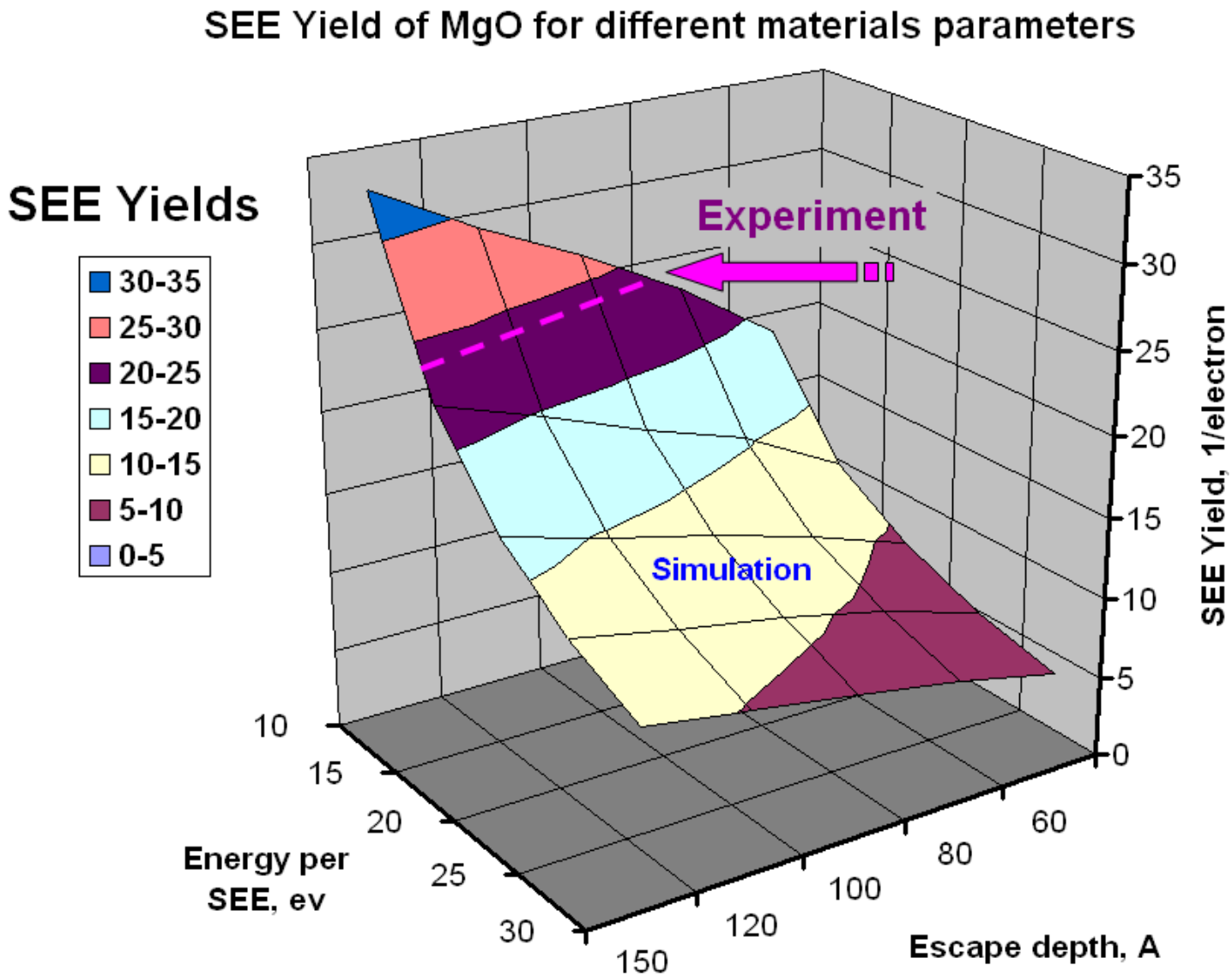
Gold SEE Yields: MC vs. Experiment



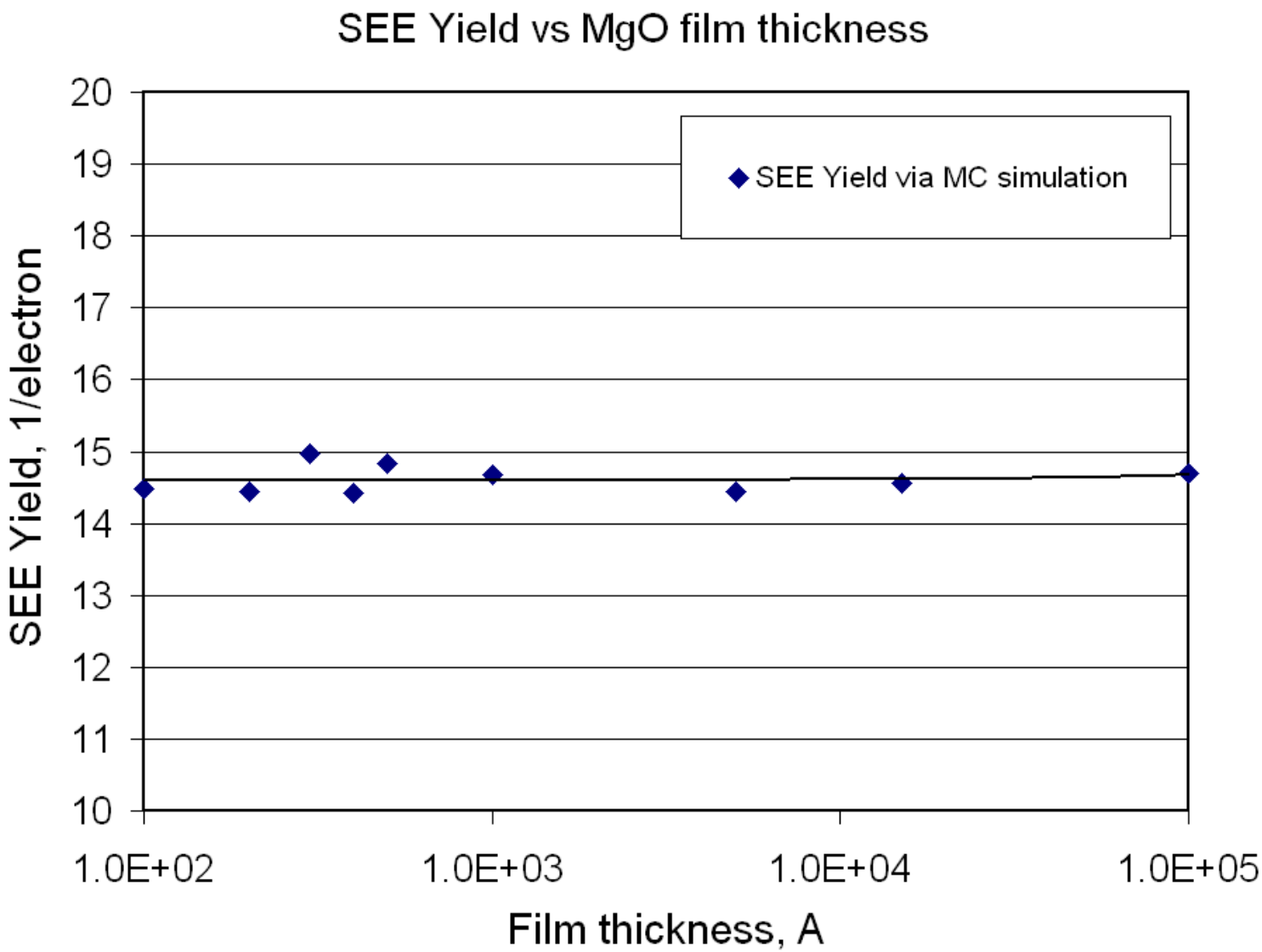
MgO SEE Yields: MC vs. Experiment



MgO SEE Yields vs. Materials constants



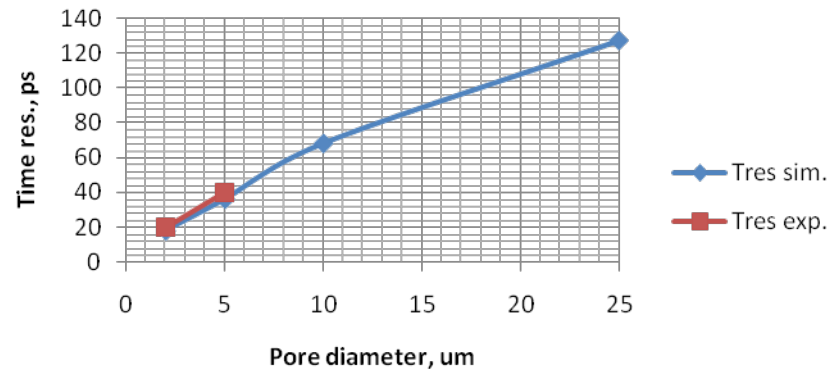
SEE Yield vs. MgO film thickness



Accomplished works. Simulations-4

DETECTOR TYPE	DETECTOR Voltage	PULSE RISE PulseWidth	Rise Time	Estimate Time Resolution at S/N=10
2μm Pore (60:1 L/D)	2200V	0.4 ns	200 ps	20 ps
5μm Pore (60:1 L/D)	2200V	0.75ns	400 ps	40 ps
10μm Chevron™	1870V	1.8 ns	283 ps	28 ps
25μm Chevron™	2000V	2.5 ns	640 ps	64 ps
Typical Channeltron™	3000V	18-20ns	3000-5000 ps	300-500ps
DiscreteDynodeMultiplier	2000-3000V	30-50 ns	6000-10000 ps	600-1000ps

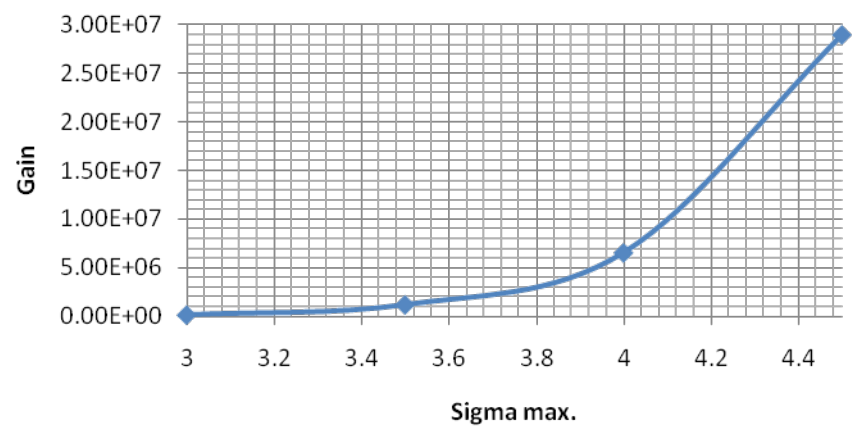
taken from http://www.burle.com/dettechbrief_4.htm



Estimation for the experimental data (red) and numerical simulations (blue) for the MCP with parameters L/D=60, Voltage U=2200V for discrimination level M0=10% ,which corresponds to the rate S/N=10.

MCP PERFORMANCE CHARACTERISTICS

Configuration	L/D Ratio	Maximum Voltage	Gain	Pulse Height
Single MCP	40:1	1000	$>4x10^3$	Neg. Exp.
	60:1	1200	$>1x10^4$	Neg. Exp.
Chevron	40:1	2000	$>4x10^6$	<175%
	60:1	2400	$>1x10^7$	<100%
Z-Stack	40:1	3000	$>3x10^7$	<120%
	60:1	3600	$>2x10^8$	<60%



Gain factor vs. the material properties for chevron-type MCP by Burle/Photonics, L/D=40. Maximal value for secondary emission yield σ_{max} = 3.5 corresponds to the SiO_2. Experiment – left, simulations – right.

Current status of the models, codes and numerical simulations

Analytical model of saturation effects

Electric field

$$E_z(z,t) = E_{0z} h_E(z,t),$$

Gain

$$M(z,t) = M_0 \frac{h_E(z,t)}{1 - \left[h_E(z,t_p) - 1\right]\exp\left(\frac{t_p - T}{\tau}\right)},$$

Shape function

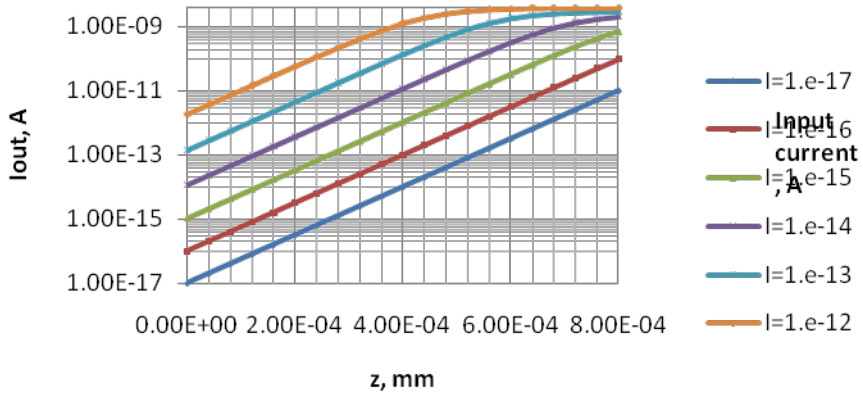
$$h_E(z,t) = \frac{\ln(M_0)}{\left[\ln(M_0) - \ln(1 + C(t)) - \ln(1 + C(t)M_0)\right]\left[1 + C(t)e^{\alpha z}\right]},$$

$$c(t) = \frac{I_0}{I_R}\left(1 - e^{-t/\tau}\right).$$

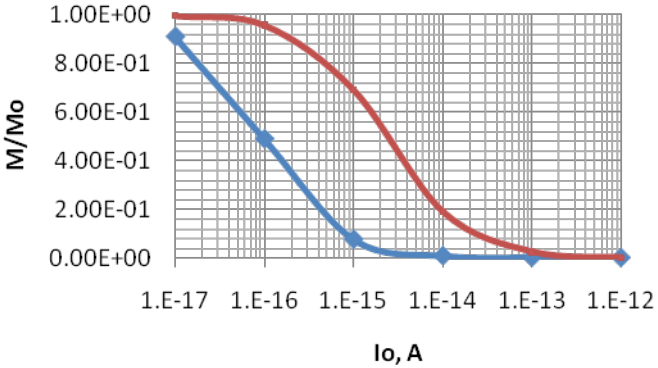
Ezo, Mo – electric field and a gain for non saturated mode;
Io – initial current of photo electrons, Ir – resistance current;
τ – relaxation time for induced positive charges.

Current status of the models, codes and numerical simulations (2)

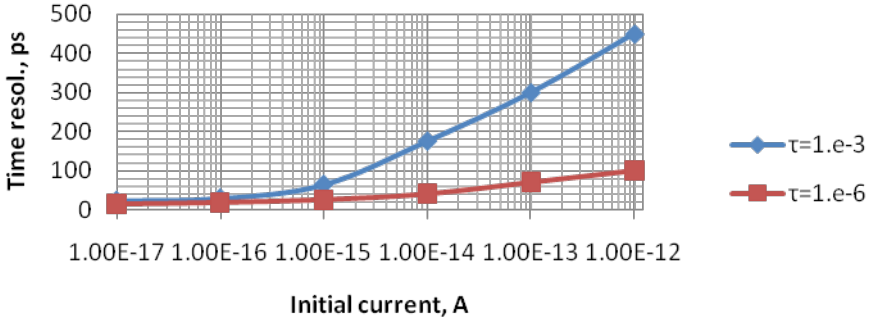
Saturation model was incorporated in the codes, and first calculations for gain & time resolution were done



MCP-current profile vs. initial current



Gain vs. initial current.
Blue – τ=1e-3, red - τ=1e-6us



Time resolution variations vs. initial current

Current status of the models, codes and numerical simulations (3)

- Model for evaluation of relaxation time – **under progress** (we should finish this task before the conference in May)
- Two types of charge carriers in GaAs are considenred: electrons and two types of holes
- Two types of geometries: cylindrical and plane
- Ambipolar drift-diffusion model is essensial
- Relaxation time is defined as numerical solution of the rate kinetics equations

Future SEE tasks

- SEE Yield's angular dependences for MgO and reference materials
- Thickness effect
- Roughness effect
- Comparison with experiment

Future simulation work. Photo-electron bunch formation

- Microscopic model of the photo-electron emission (Zeke, Klaus, Bernard);
- Angular and energy distribution for the photo-emitted electrons (Zeke);
- Bunch formation for electron optical calculations (Valentin);

Simulation Tasks

- **Existing technologies**

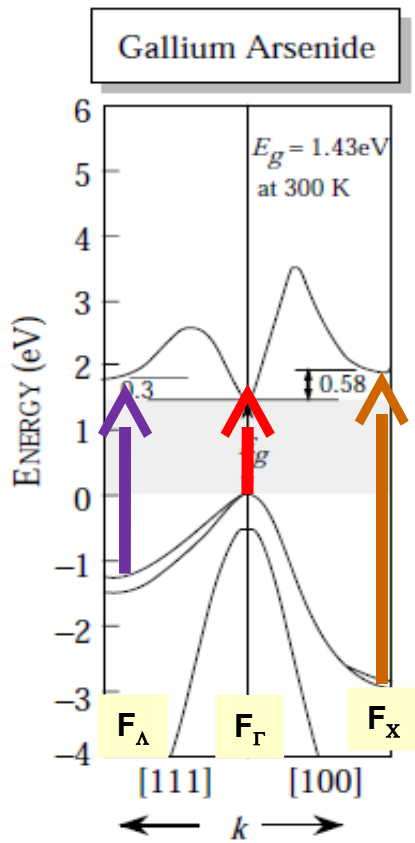
1. Electron/hole diffusion lengths in the bulk semi-conductors
2. Surface roughness vs reflectivity
3. Trajectories of PE to the MCP surface - Valentin

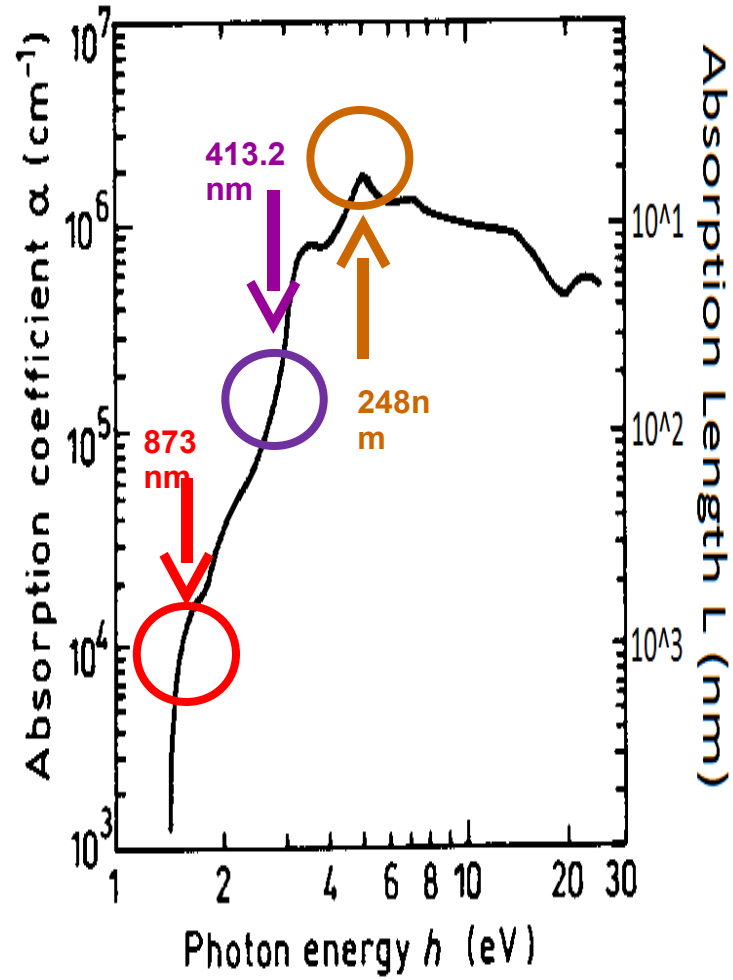
- **Prospective technologies**

1. Ab-initio F^{X}, F^{G}, F^{L} (Bernhard)
2. Optimization of the NEA of the photo-cathode materials (Bernhard)
3. Electron / hole diffusion lengths in the heavily doped GaAs (Klaus)
4. Dopant profiles, electric fields by using a software (Klaus)
5. Surface roughness influence on the photon reflectivity or transmission (Klaus)
6. Trajectory studies for new materials and new morphology - Valentin

Ab-initio simulations

- **Ab-initio of photonic, electronic, and defect properties of the nano-, multi-layered, mono- and poly-crystalline GaAs-Cs-O, doped CsO, TiO2 and NEA materials - *Bernhard***
- **The overall structure of the photocathode will be optimized by COMSOL multiphysics package**





Tasks added by Bernhard

- **Optimization of Photocathodes for X-rays: how can we improve the X-ray stopping power while maintaining fast response?**

- **This is something fundamental, and just food for thought:**
  - ***we are assuming that a photon is absorbed in the photocathode, and an electron then has to diffuse (or be driven by E-field) from there to the surface***

Question: are there other possibilities?

- Bernhard

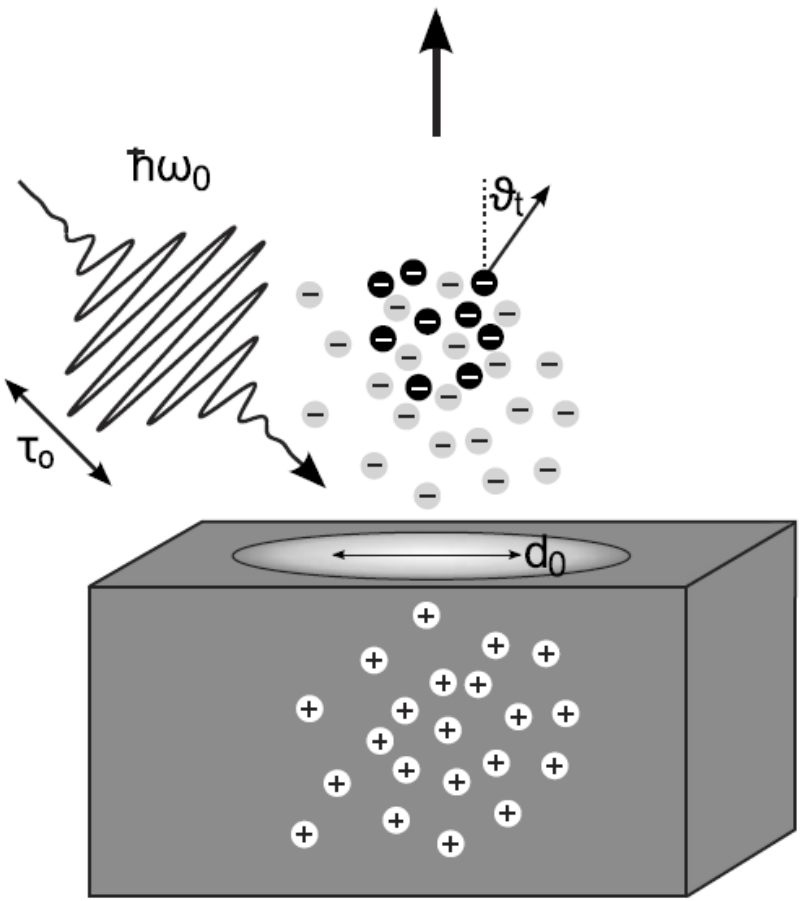
- Can electron emission work in other ways, such as can absorption of a photon deep in the cathode trigger release of an electron from the surface without electron diffusion – for example through E-fields inside the cathode? Enhancement vs noise

- Can we make a structure with internal gain? Pillar?

- Can electron emission be triggered from a nonlinear device, similarly to a laser diode operating right at the lasing threshold?

Space-Charge Effect in PC

- The higher the number of cloud electrons per pulse *Nc* the stronger is the space-charge effect.
- Non-negligible space-charge effects occur already at rather low values of *Nc* of about 1000*e* per pulse [1].
- APS experiments have estimated *Nc* per pulse >> 1000e [2].



APS experimental data

$Q = I_{max} * \tau_0 = 140\mu A * 80\ ps = 1.12e\text{-}14\ C$

Nc = 7e4 per pulse

[1] J. Zhou et al, J. El. Spectr.Rel.Phen. 2005.
[2] Matt Wetstein, APS, Nc=7e4 per pulse

Space-Charge Limited Potential

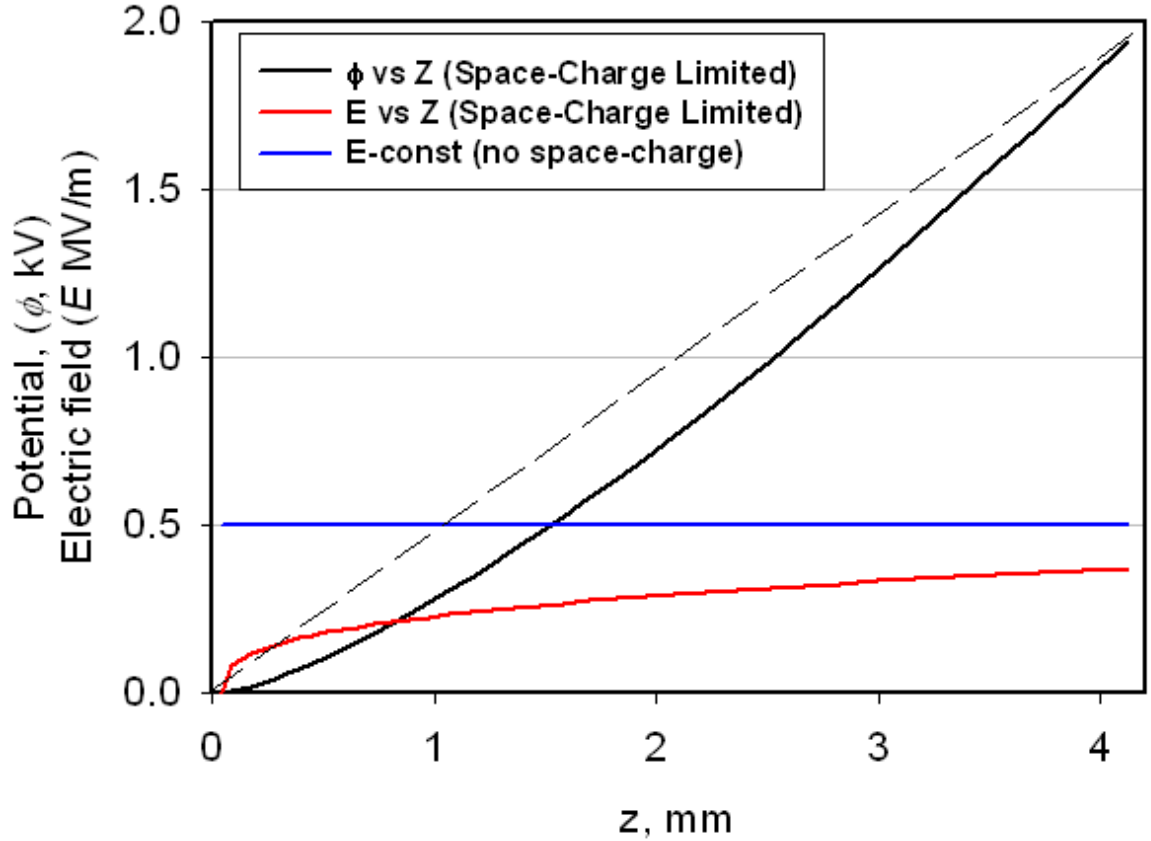
Child-Langmuir equation

$$J_{SCL} = \frac{4}{9}\varepsilon_0\sqrt{\frac{2e}{m}}\cdot\frac{V^{3/2}}{D^2},$$

$$\phi = V\left(\frac{z}{D}\right)^{4/3},$$

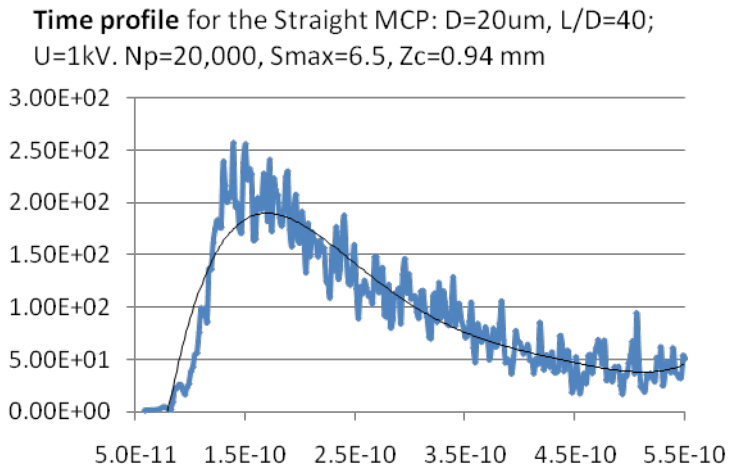
$$E = \frac{4}{3}\frac{V}{D}\left(\frac{z}{D}\right)^{1/3}.$$

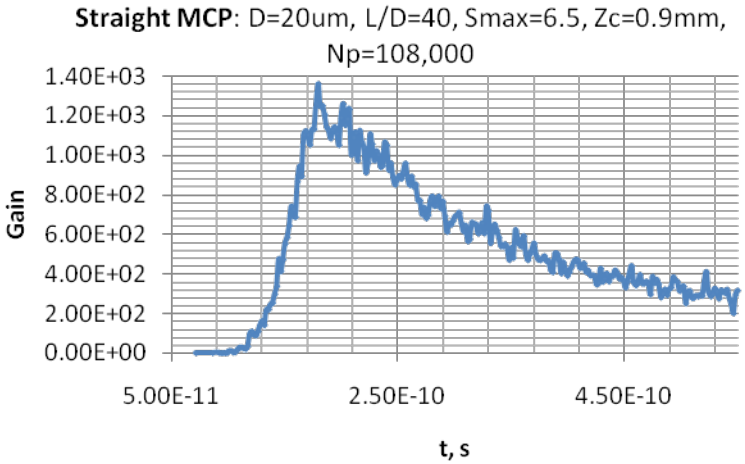
Electric field between photocathode and anode



Future simulation work -2

- Noise simulation & its influence on the time resolution





- Capturing optimization for funnel-type MCP (Valentin).

Problems and challenges

- Field calculations for funnel type MCP (Valentin);
- First strike optimization (Valentin);
- Heating effects (Zeke, Valentin);
- Aging effects due thermal effects & ion-feedback (Zeke, Bernhard, Slade, Klaus?)
- Aging effects to PC due to gas in the space between PC and MCP (Zeke, Slade) .