Simulation of Timing Determinants: Predictions and Results

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Presented to: The Factors that Limit Time Resolution in Photodetectors, Workshop 28-29 April 2011

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Perspective

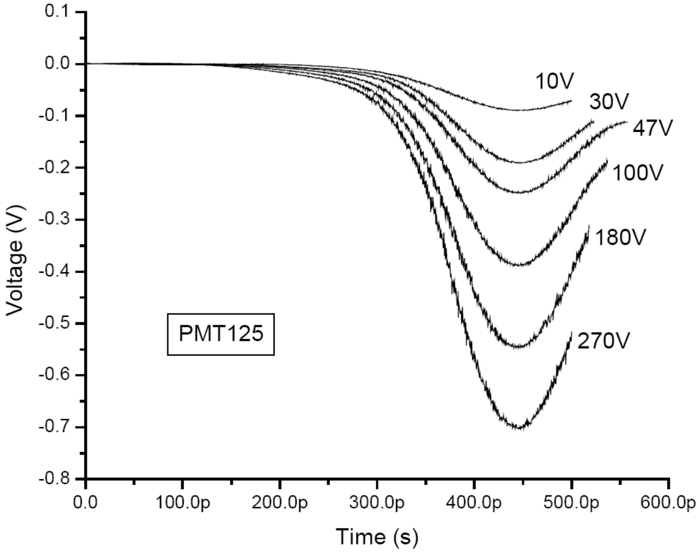
Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful.

- Box & Draper, *Empirical Model-Building*, p. 74

MCP-PMT timing (rise time) breakdown

J. Milnes and J. Howorth, "Picosecond time response characteristics of microchannel plate PMT detectors," Proc. SPIE 5580, 730 (2005); doi:10.1117/12.568180

- 1. Cathode Gap – Small effect
  - electrons emitted from cathode have a small energy (< 2eV) vs. the gap field (> 200eV).
- 2. MCP Stack
- 3. Anode Gap - Similar to cathode
  - except electrons leaving MCP have significant variation in lateral velocity



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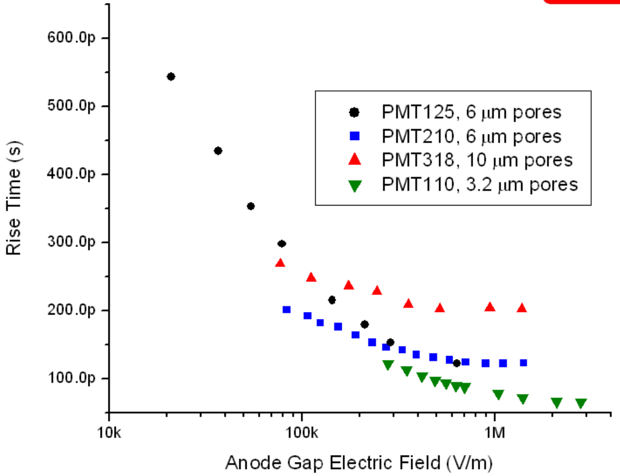


- "We have found that the rise time of MCP-based PMT detectors is principally governed by the variation in transit time through the MCP pores and the variation in exit velocity from the MCP stack."

MCP– Main source of rise time spread

J. Milnes & J. Howorth, "Picosecond time response characteristics of microchannel plate PMT detectors," Proc. SPIE 5580, 730 (2005); doi:10.1117/12.568180
S. Matsuura, S. Umebayashi, C. Okuyama, K. Oba, "CHARACTERISTICS OF THE NEWLY DEVELOPEDMCP AND ITS ASSEMBLY," IEEE Trans. Nuc. Sci. Vol. NS-32, 1, February 1985

- Primarily due to the many different possible path lengths (and hence transit times) of the electron avalanche through the MCP pores. Main factors:
  - Pore size: Using narrow pore MCPs would be expected to reduce the path length variation.
  - Bias angle: Uniformity of cascade initiation
  - Number of MCPs in the stack produce wider variation of path length and is therefore expected to increase rise time.
- The variation in transit time through the MCP pores is affected more by size and bias angle of the MCP pores rather than the number of MCPs.
- The spread of the rise time caused by variations in the exit velocity from the MCP stack can be severely reduced by increasing the electric field from the MCP to the anode.

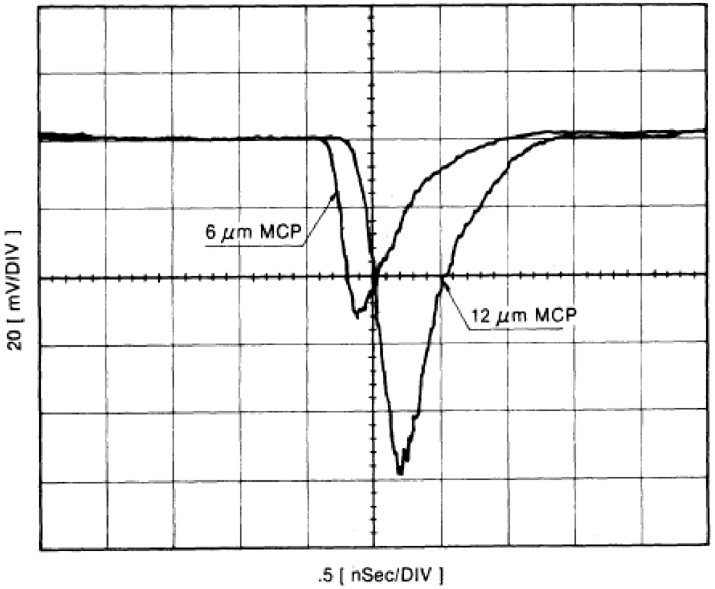
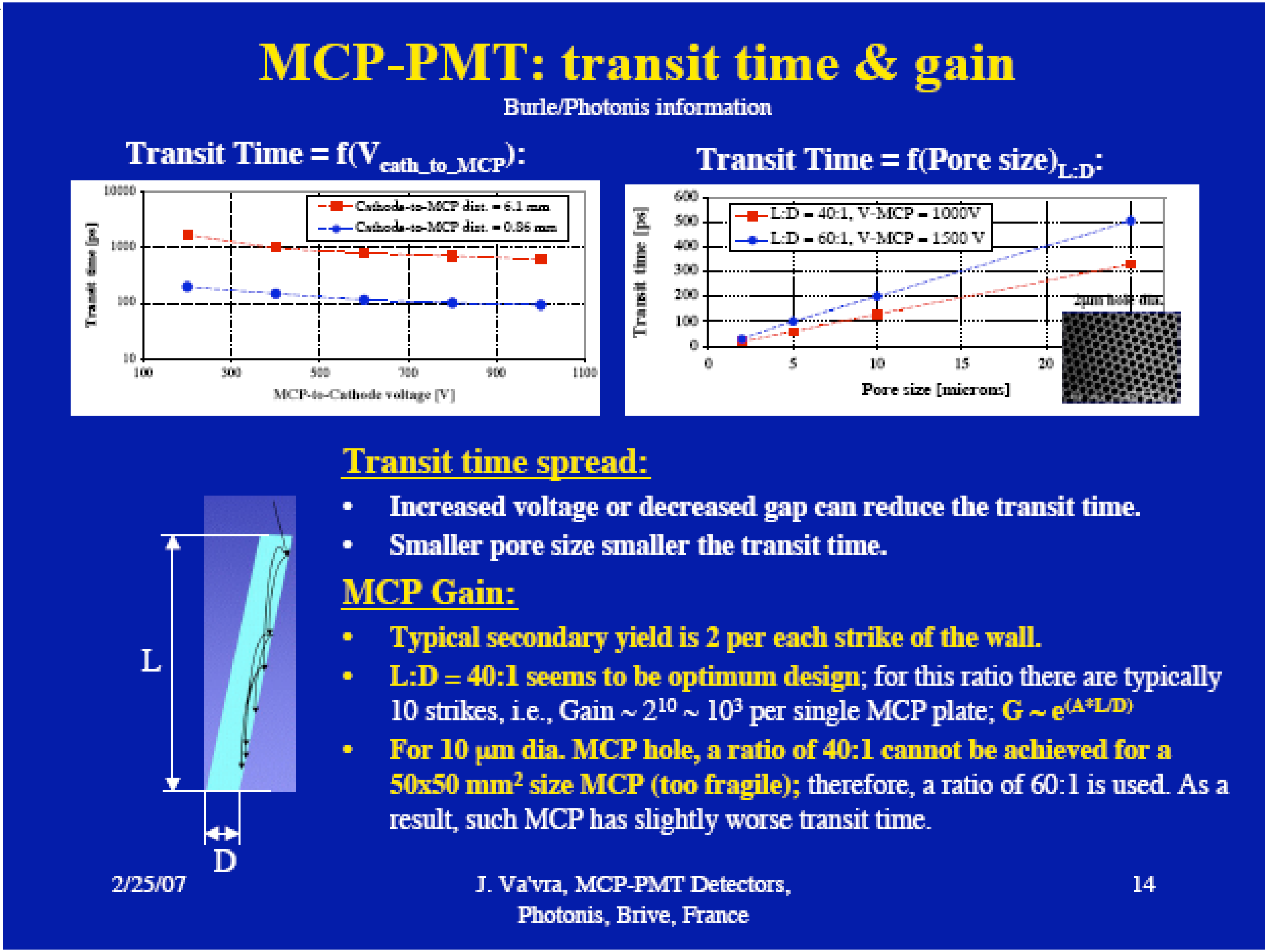


Fig. 13. Impulse responses of 2-stage 6μm MCP-PMT and 2-stage 12μm MCP-PMT

Table 1 Comparison of timing characteristics of 2-stage 6μm MCP-PMT and 2-stage 12μm MCP-PMT

		6 μm Channel	12 μm Channel
RISE TIME	(nSec)	.167	.245
FALL TIME	(nSec)	.721	.716
TRANSIT TIME	(nSec)	.406	.650
TRANSIT TIME SPREAD	(nSec)	.067	.081

Experimental results: MCP-PMT



MCP-PMT: transit time & gain

Burle/Photonis information

Transit Time = f($V_{cath\_to\_MCP}$):

Transit Time = f(Pore size)$_{L:D}$:

Transit time spread:

- Increased voltage or decreased gap can reduce the transit time.
- Smaller pore size smaller the transit time.

MCP Gain:

- Typical secondary yield is 2 per each strike of the wall.
- L:D = 40:1 seems to be optimum design; for this ratio there are typically 10 strikes, i.e., Gain ~ 2^{10} ~ 10^3 per single MCP plate; G ~ $e^{(A*L/D)}$
- For 10 µm dia. MCP hole, a ratio of 40:1 cannot be achieved for a 50x50 mm^2 size MCP (too fragile); therefore, a ratio of 60:1 is used. As a result, such MCP has slightly worse transit time.

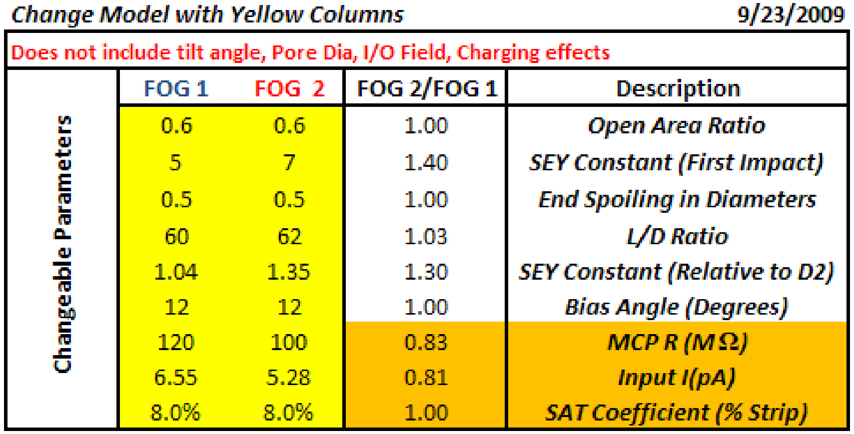
2/25/07 J. Va'vra, MCP-PMT Detectors, Photonis, Brive, France 14

CASCADE First Order Gain (FOG) Analysis

1. Adams, J.; Manley, B. W., "The Mechanism of Channel Electron Multiplication,"IEEE Trans. Nuc. Sci., v13, 3, p88

- e. g. Adams[1]

$$G = \left(\frac{KV_o^{\,2}}{4V\alpha^2}\right)^{\frac{4V\alpha^2}{V_o}}$$



Change Model with Yellow Columns 9/23/2009

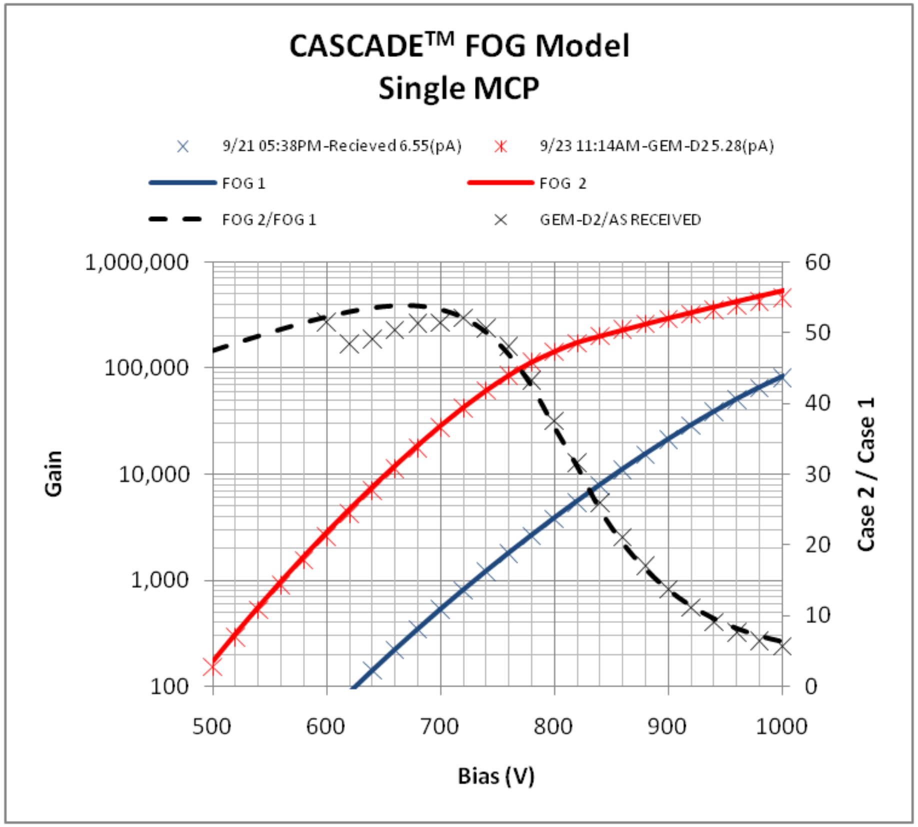
Does not include tilt angle, Pore Dia, I/O Field, Charging effects

	FOG 1	FOG 2	FOG 2/FOG 1	Description
Changeable Parameters	0.6	0.6	1.00	*Open Area Ratio*
	5	7	1.40	*SEY Constant (First Impact)*
	0.5	0.5	1.00	*End Spoiling in Diameters*
	60	62	1.03	*L/D Ratio*
	1.04	1.35	1.30	*SEY Constant (Relative to D2)*
	12	12	1.00	*Bias Angle (Degrees)*
	120	100	0.83	*MCP R (MΩ)*
	6.55	5.28	0.81	*Input I(pA)*
	8.0%	8.0%	1.00	*SAT Coefficient (% Strip)*

FOG Analysis Results For GEM-D2

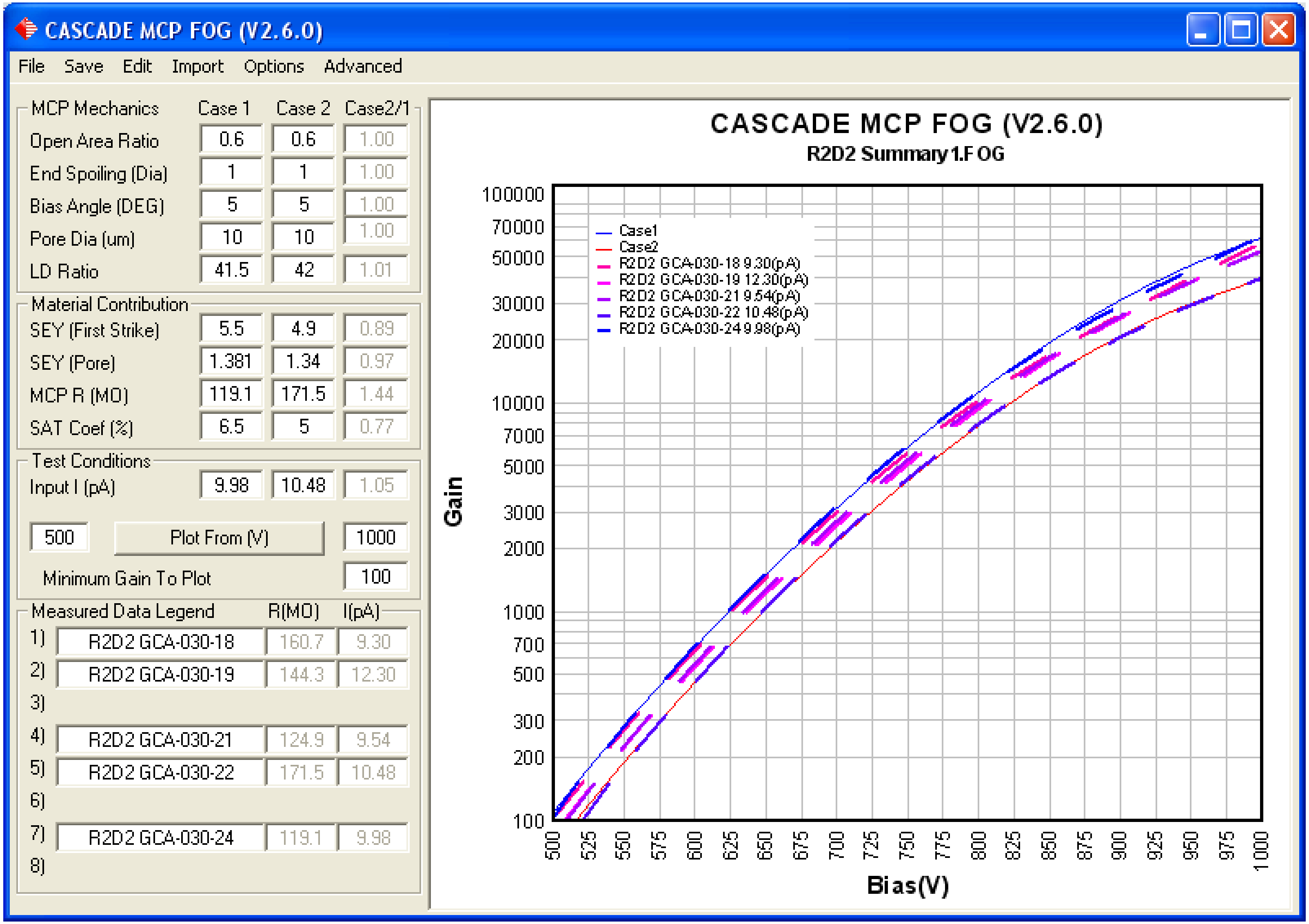
1. 40% increase in first strike SEY
2. 30% increase in pore cascade SEY
3. 3 % increase in apparent LD ratio

- Before and After Emissive Coating - 60:1 LD, 12um Pitch, 12 Degree Bias



Solid line is modeled

CASCADE FOG 40:1 LD 10 um Pore MCP



MCP Mechanics	Case 1	Case 2	Case2/1
Open Area Ratio	0.6	0.6	1.00
End Spoiling (Dia)	1	1	1.00
Bias Angle (DEG)	5	5	1.00
Pore Dia (um)	10	10	1.00
LD Ratio	41.5	42	1.01
Material Contribution			
SEY (First Strike)	5.5	4.9	0.89
SEY (Pore)	1.381	1.34	0.97
MCP R (MΩ)	119.1	171.5	1.44
SAT Coef (%)	6.5	5	0.77
Test Conditions			
Input I (pA)	9.98	10.48	1.05

Plot From (V): 500 to 1000

Minimum Gain To Plot: 100

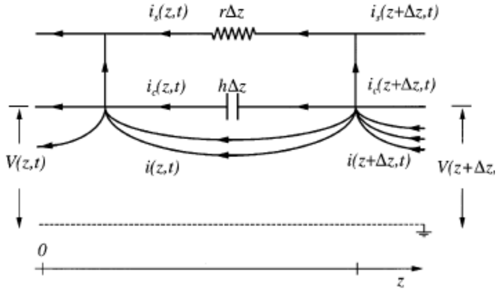
Measured Data Legend		R(MΩ)	I(pA)
1)	R2D2 GCA-030-18	160.7	9.30
2)	R2D2 GCA-030-19	144.3	12.30
3)			
4)	R2D2 GCA-030-21	124.9	9.54
5)	R2D2 GCA-030-22	171.5	10.48
6)			
7)	R2D2 GCA-030-24	119.1	9.98
8)			

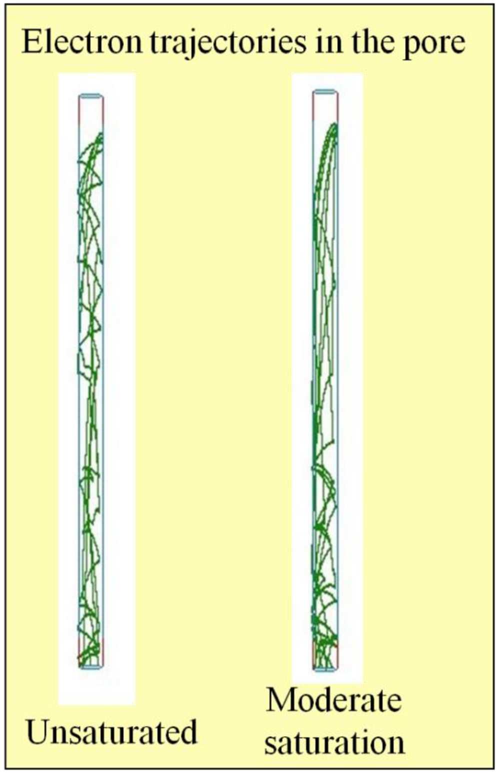
Models – (Tremsin) Macro Giudicotti[1]

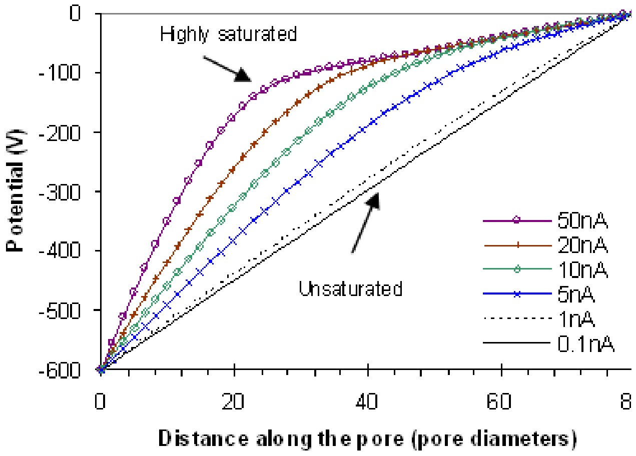
L. Giudicotti, Nucl. Instr. Meth. A 480 (2002) 670.

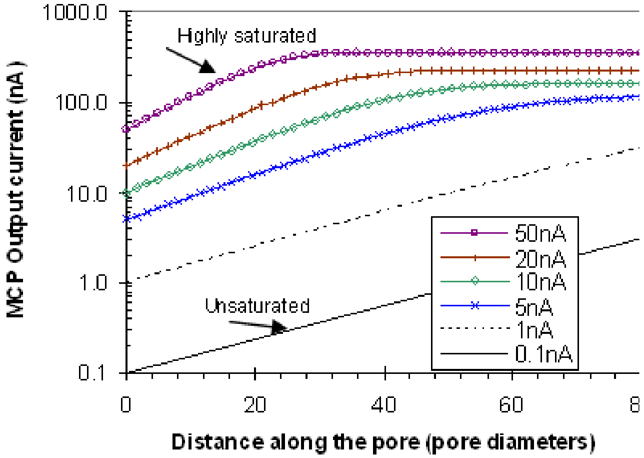
3D microscopic model with “super-electron”.

- Transmission Line

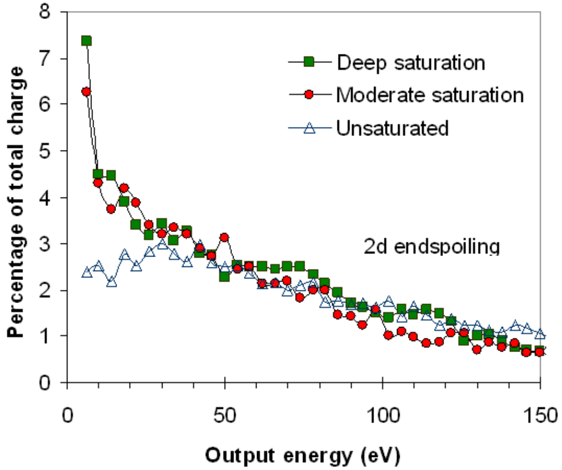




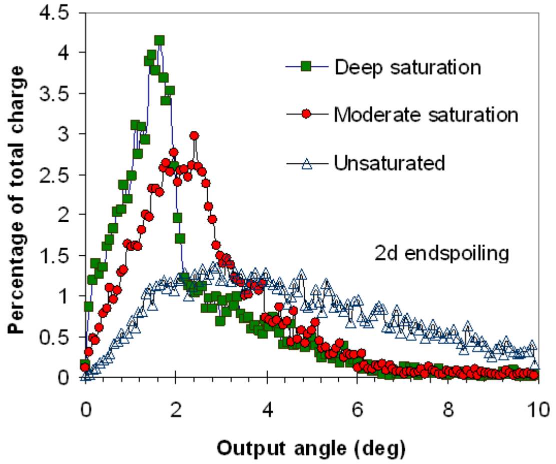




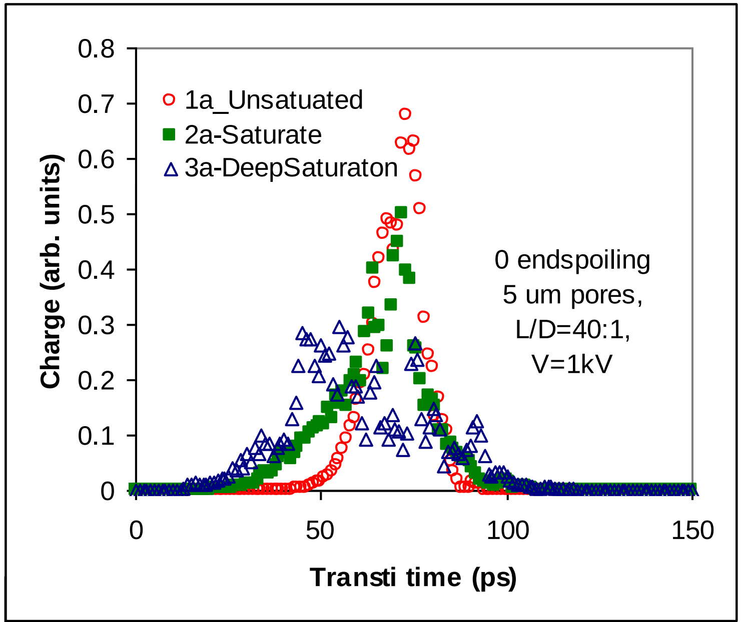
Output energy distribution

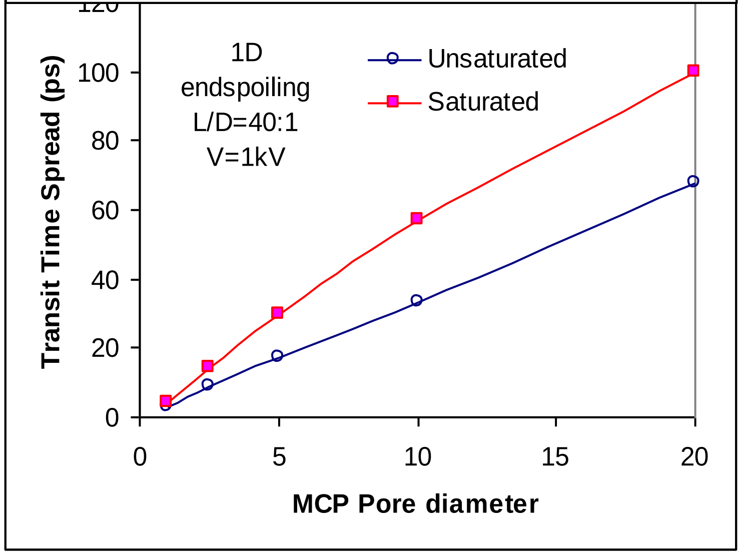


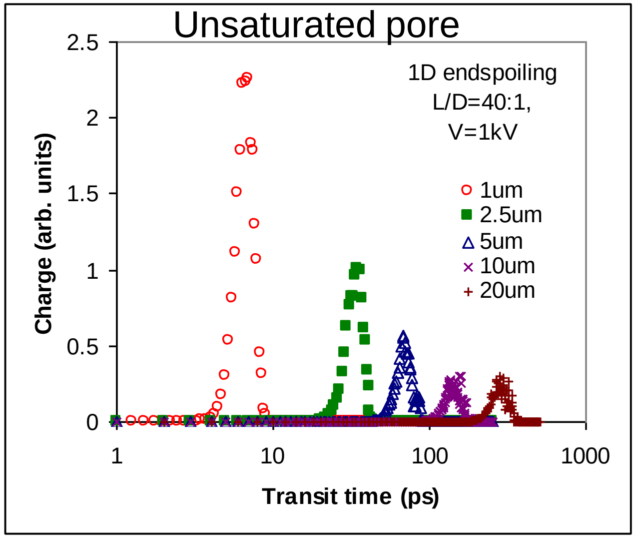
Output angular distribution

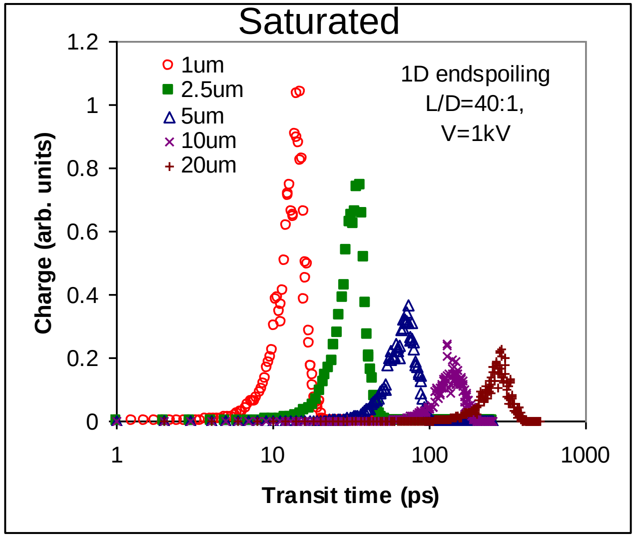


Macro-Micro Treatment TTS vs. pore diameter









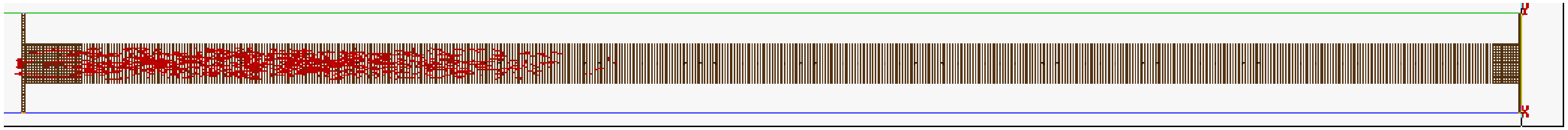
MCP CASCADE Simulation

About the model:

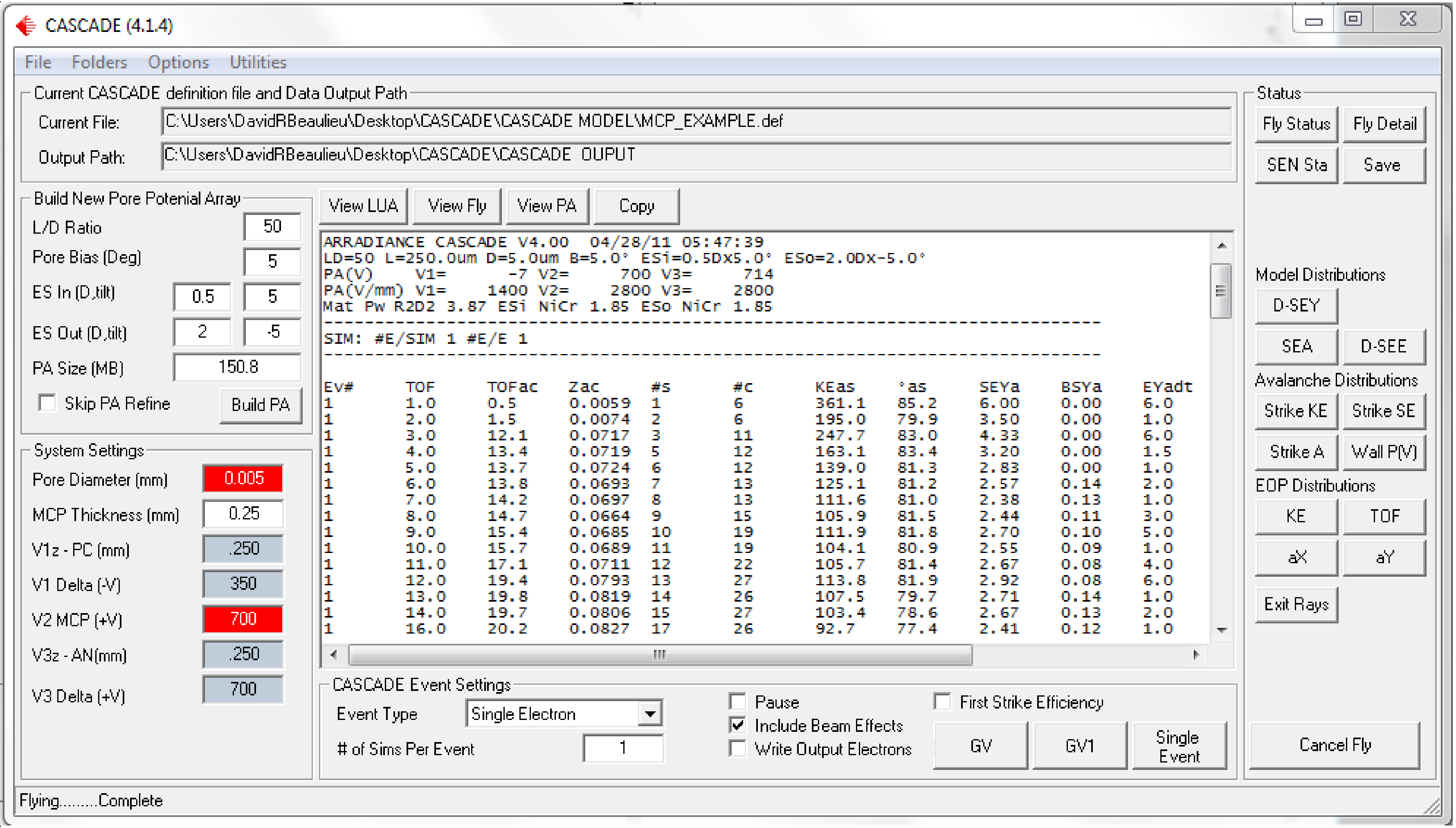
- MCP Cascade model is a single electron event Monte Carlo simulation of a an MCP pore and extraction parameters
- At a microscopic level, the model accounts for the following.
  - 3D geometry and potential array for flight characteristics within, and outside the pore
  - End spoiling (extraction) fields and penetration
  - Material SE characteristics including yield and SE energy
  - Cosine angular distribution of SE including normal vector correction of surface strikes based on geometry
  - Real time (event based) beam potentials and effects on SE creation
  - Real time (event based) wall charging potentials and effects on SE creation

The model predicts and reports:

- Single event gain based on input geometry, materials, and MCP bias potentials and extraction potentials
- Particle output statistics at the end of the pore, and remote anode including
  - Energy distributions
  - x', y', and r' angle distribution
  - x, y, and z velocity distribution
  - x, y, and z positions and distribution
  - Time of flight distribution
  - Tab delimited particle output files



Standard User Interface CASCADE™



Current CASCADE definition file and Data Output Path

Current File: C:\Users\DavidRBeaulieu\Desktop\CASCADE\CASCADE MODEL\MCP_EXAMPLE.def

Output Path: C:\Users\DavidRBeaulieu\Desktop\CASCADE\CASCADE OUPUT

Build New Pore Potenial Array

L/D Ratio 50

Pore Bias (Deg) 5

ES In (D,tilt) 0.5 5

ES Out (D,tilt) 2 -5

PA Size (MB) 150.8

☐ Skip PA Refine

System Settings

Pore Diameter (mm) 0.005

MCP Thickness (mm) 0.25

V1z - PC (mm) .250

V1 Delta (-V) 350

V2 MCP (+V) 700

V3z - AN(mm) .250

V3 Delta (+V) 700

```
ARRADIANCE CASCADE V4.00  04/28/11 05:47:39
LD=50 L=250.0um D=5.0um B=5.0° ESi=0.5Dx5.0° ESo=2.0Dx-5.0°
PA(V)     V1=       -7 V2=      700 V3=      714
PA(V/mm)  V1=     1400 V2=     2800 V3=     2800
Mat Pw R2D2 3.87 ESi NiCr 1.85 ESo NiCr 1.85
------------------------------------------------------------------------------------------------
SIM: #E/SIM 1 #E/E 1
------------------------------------------------------------------------------------------------

Ev#       TOF       TOFac     Zac       #s        #c        KEas      °as       SEYa      BSYa      EYadt
1         1.0       0.5       0.0059    1         6         361.1     85.2      6.00      0.00      6.0
1         2.0       1.5       0.0074    2         6         195.0     79.9      3.50      0.00      1.0
1         3.0       12.1      0.0717    3         11        247.7     83.0      4.33      0.00      6.0
1         4.0       13.4      0.0719    5         12        163.1     83.4      3.20      0.00      1.5
1         5.0       13.7      0.0724    6         12        139.0     81.3      2.83      0.00      1.0
1         6.0       13.8      0.0693    7         13        125.1     81.2      2.57      0.14      2.0
1         7.0       14.2      0.0697    8         13        111.6     81.0      2.38      0.13      1.0
1         8.0       14.7      0.0664    9         15        105.9     81.5      2.44      0.11      3.0
1         9.0       15.4      0.0685    10        19        111.9     81.8      2.70      0.10      5.0
1         10.0      15.7      0.0689    11        19        104.1     80.9      2.55      0.09      1.0
1         11.0      17.1      0.0711    12        22        105.7     81.4      2.67      0.08      4.0
1         12.0      19.4      0.0793    13        27        113.8     81.9      2.92      0.08      6.0
1         13.0      19.8      0.0819    14        26        107.5     79.7      2.71      0.14      1.0
1         14.0      19.7      0.0806    15        27        103.4     78.6      2.67      0.13      2.0
1         16.0      20.2      0.0827    17        26        92.7      77.4      2.41      0.12      1.0
```

CASCADE Event Settings

Event Type: Single Electron

# of Sims Per Event: 1

☐ Pause

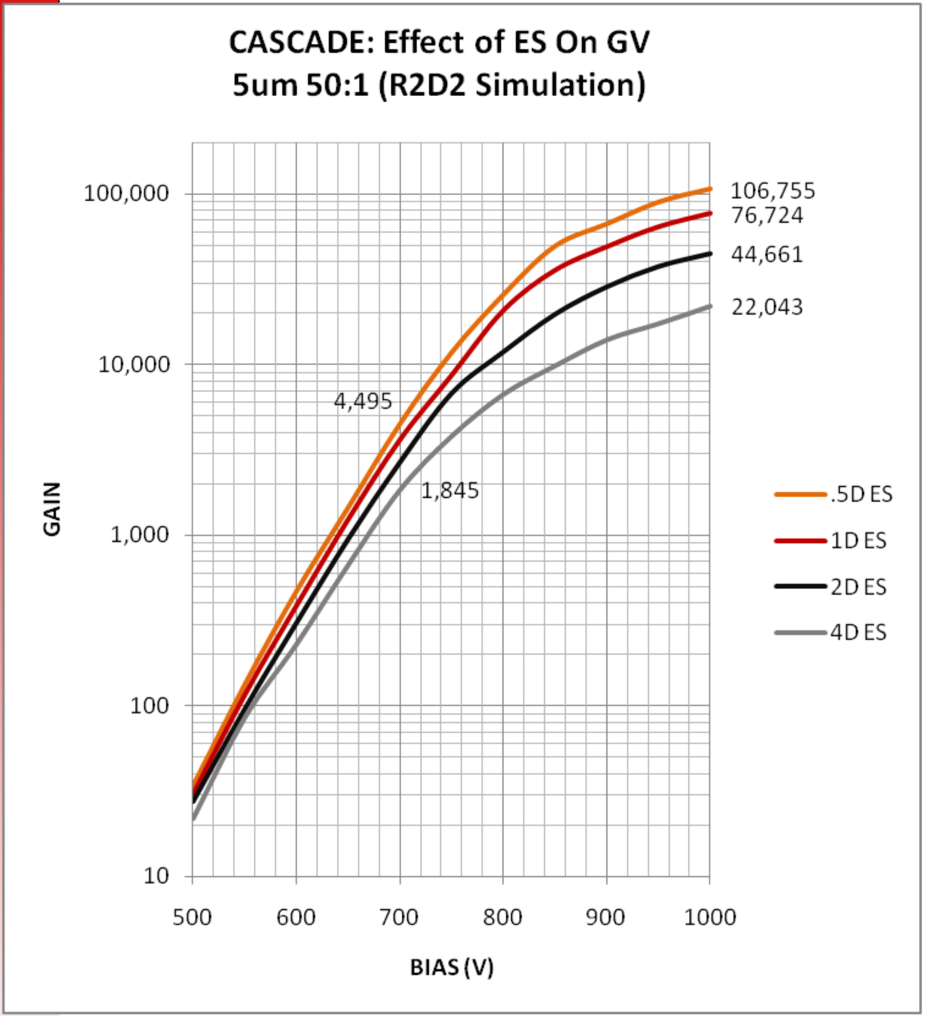
☑ Include Beam Effects

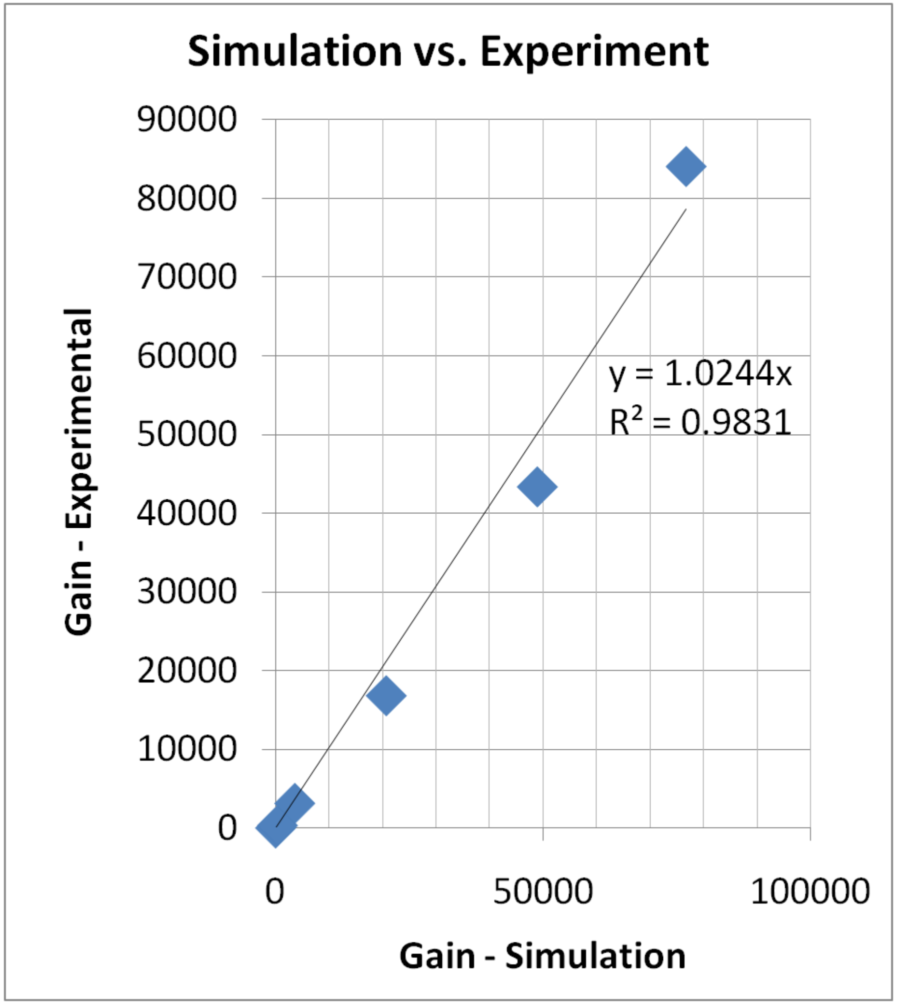
☐ Write Output Electrons

☐ First Strike Efficiency

Flying.........Complete

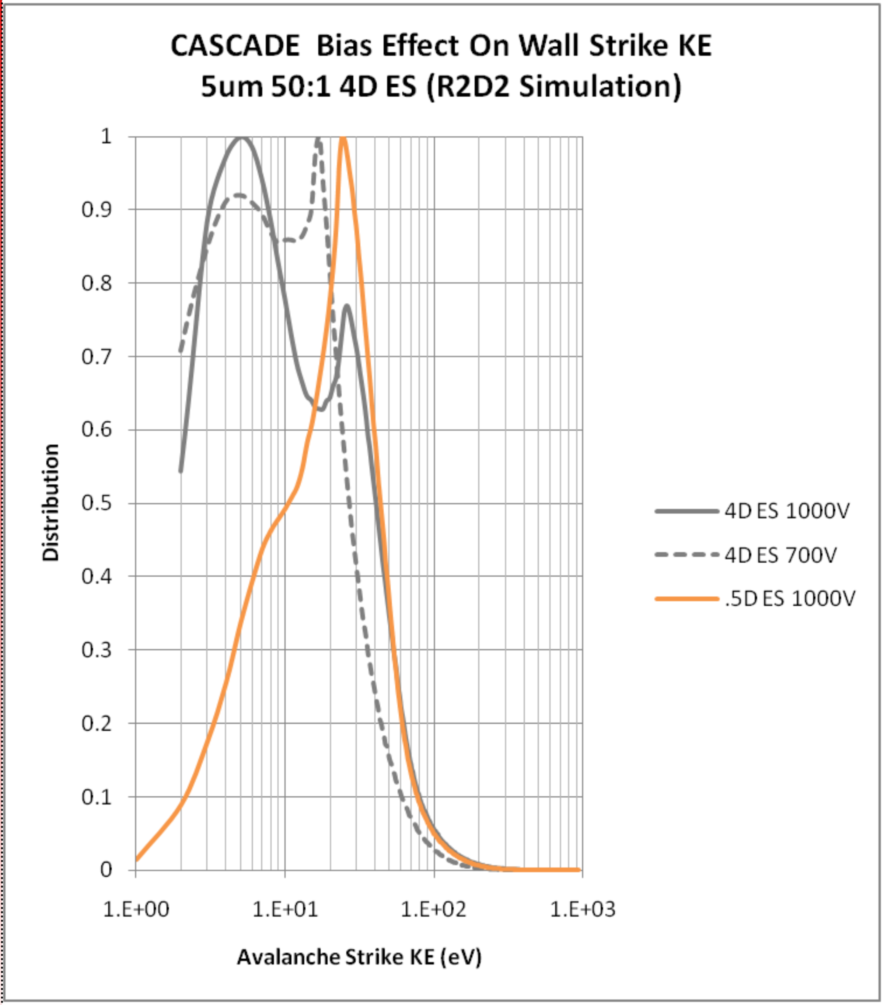
MCP CASCADE Experimental Agreement: Gain vs Bias & Endspoiling



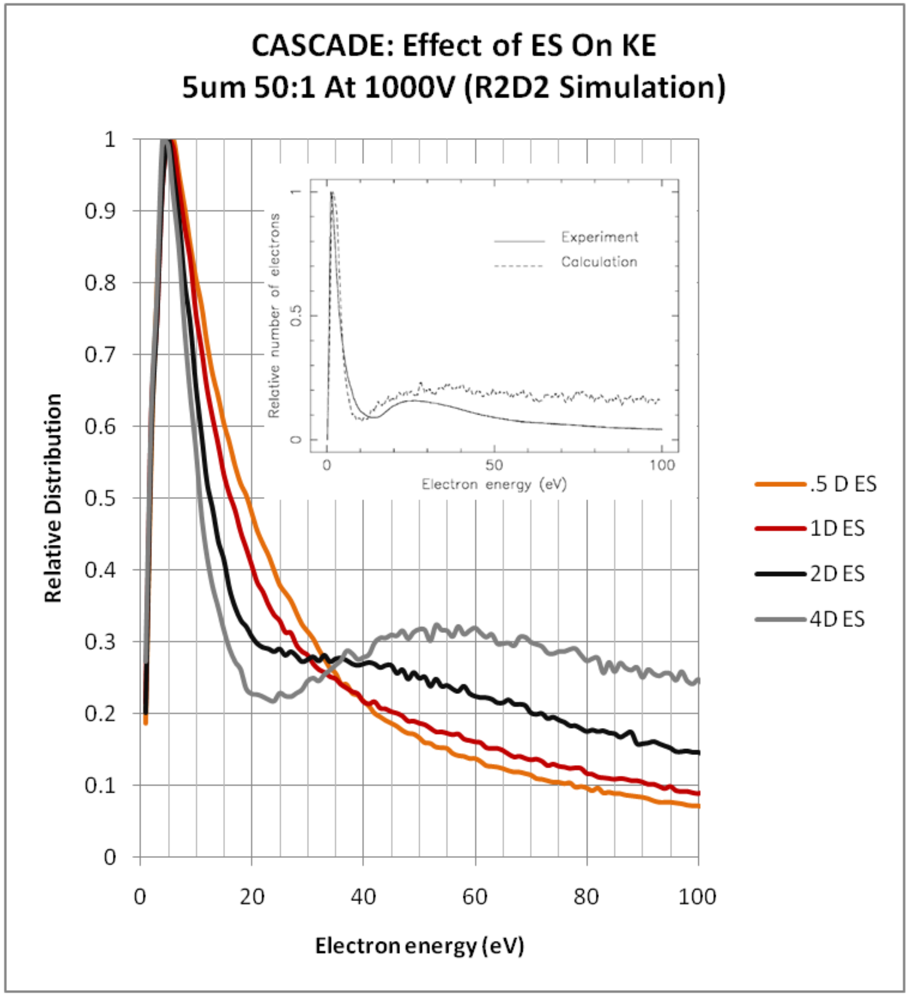


MCP Cascade: Effect of Bias and Endspoiling

inset, from G.J. Price, G.W. Fraser / Nuclear Instruments and Methods in Physics Research A 474 (2001) 188–196

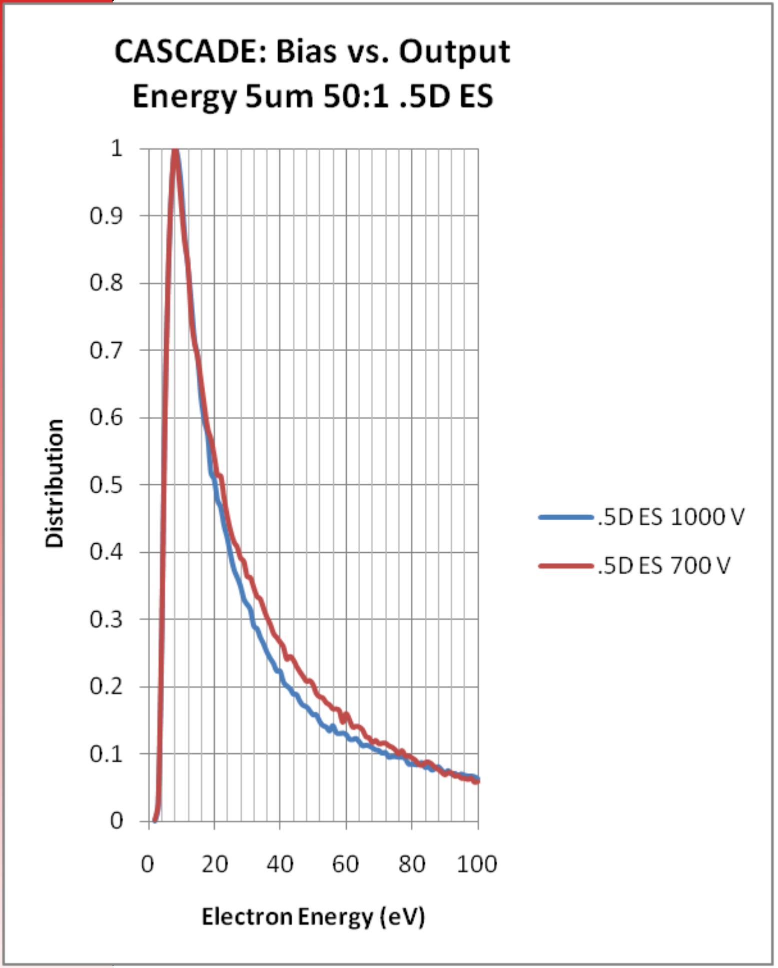


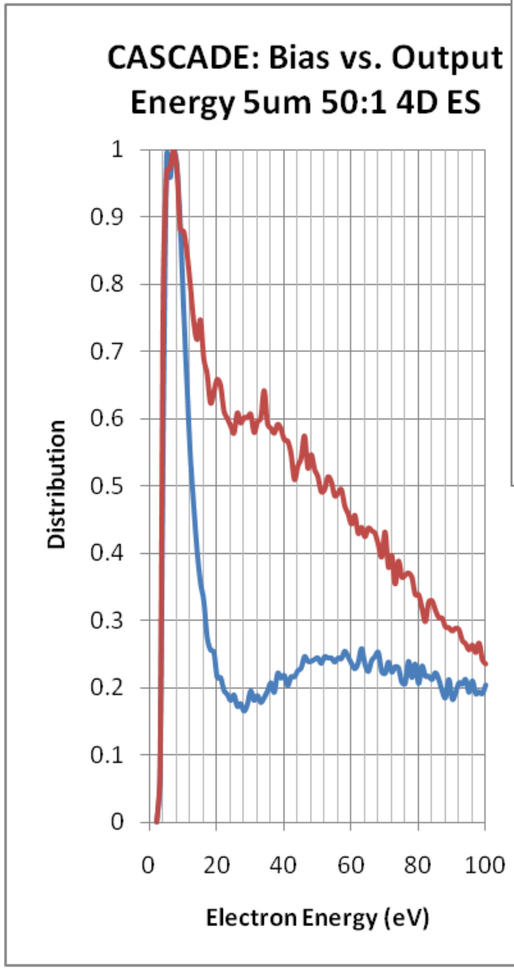
CASCADE Bias Effect On Wall Strike KE
5um 50:1 4D ES (R2D2 Simulation)

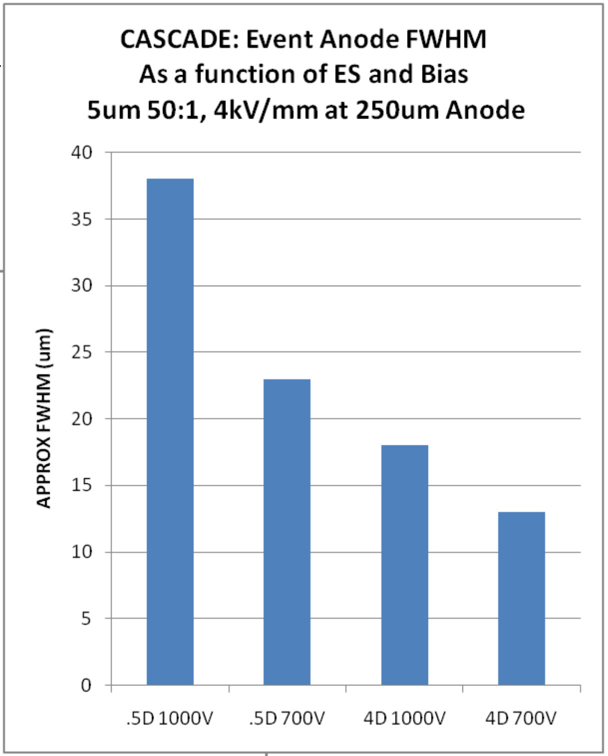


CASCADE: Effect of ES On KE
5um 50:1 At 1000V (R2D2 Simulation)

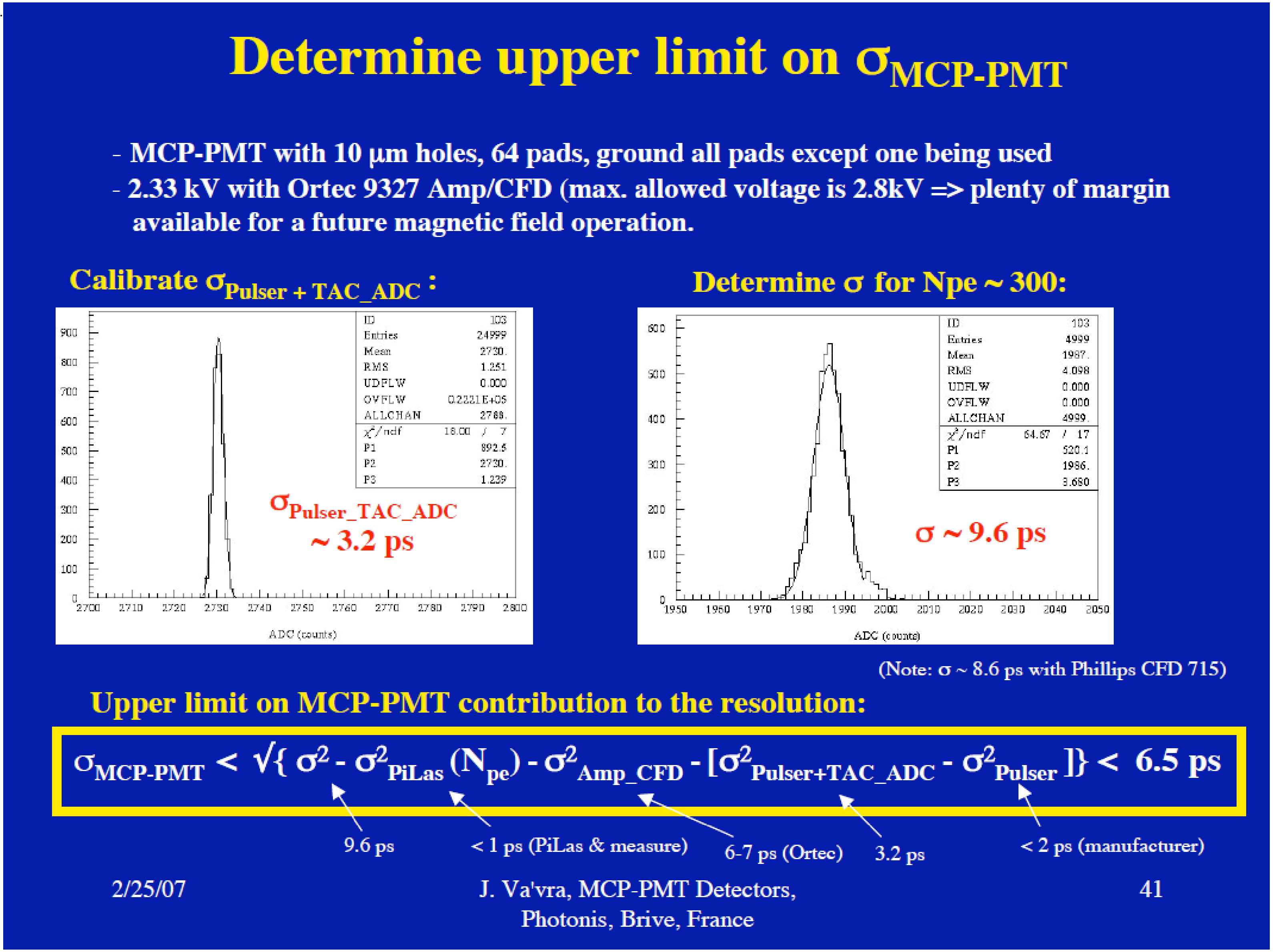
CASCADE: Prediction of Bias & Endspoiling







We can we get to…?



Determine upper limit on $\sigma_{MCP\text{-}PMT}$

- MCP-PMT with 10 µm holes, 64 pads, ground all pads except one being used
- 2.33 kV with Ortec 9327 Amp/CFD (max. allowed voltage is 2.8kV => plenty of margin available for a future magnetic field operation.

Calibrate $\sigma_{Pulser + TAC\_ADC}$:

Determine σ for Npe ~ 300:

(Note: σ ~ 8.6 ps with Phillips CFD 715)

Upper limit on MCP-PMT contribution to the resolution:

$$\boxed{\sigma_{MCP\text{-}PMT} < \sqrt{\{\underset{\uparrow}{\sigma^2} - \underset{\uparrow}{\sigma^2_{PiLas}}(N_{pe}) - \underset{\uparrow}{\sigma^2_{Amp\_CFD}} - [\underset{\uparrow}{\sigma^2_{Pulser+TAC\_ADC}} - \underset{\uparrow}{\sigma^2_{Pulser}}]\}} < 6.5 \text{ ps}}$$

9.6 ps

< 1 ps (PiLas & measure)

6-7 ps (Ortec)

3.2 ps

< 2 ps (manufacturer)

2/25/07

J. Va'vra, MCP-PMT Detectors,
Photonis, Brive, France

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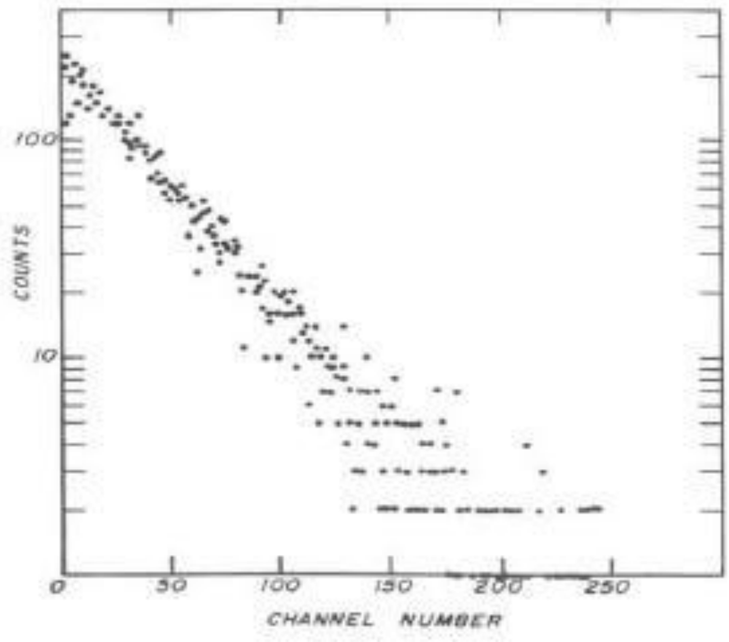
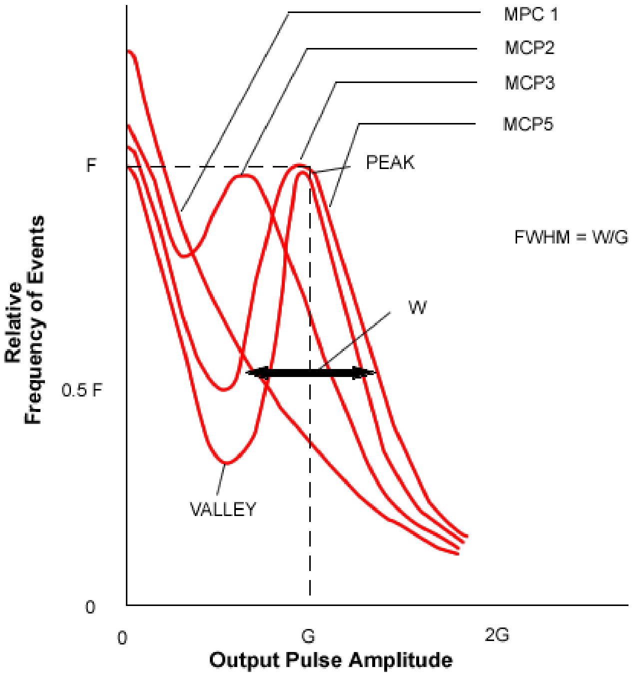
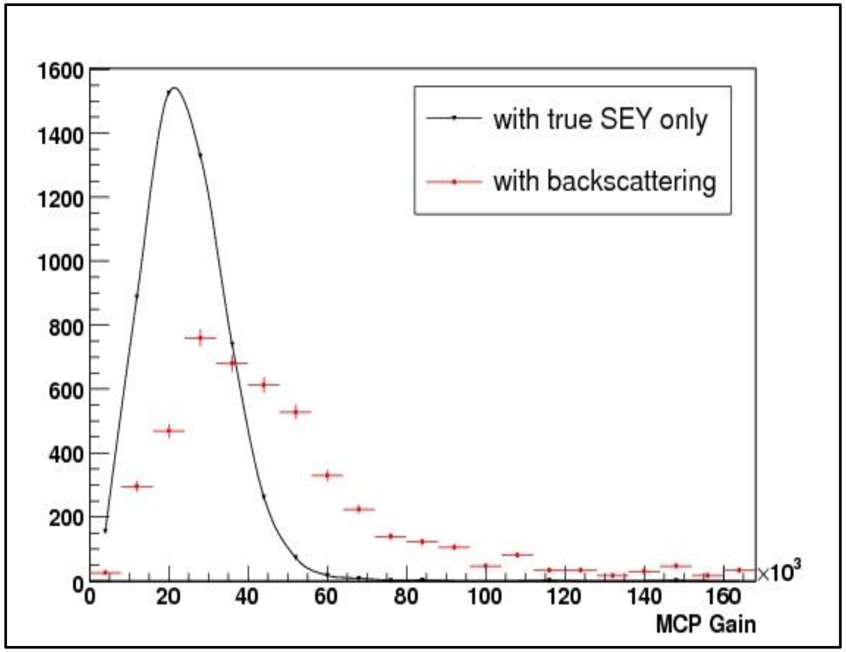
PHD

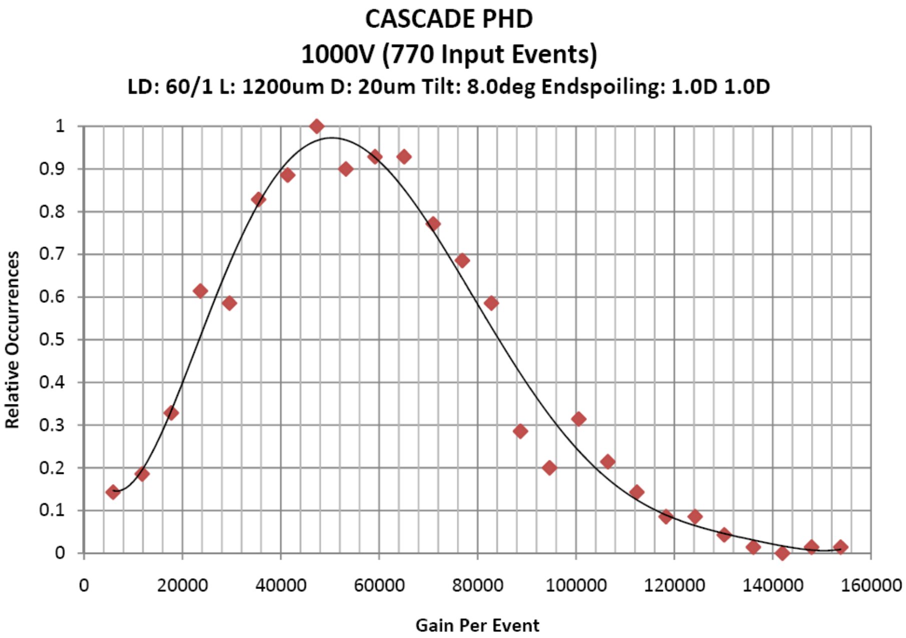
J. WIZA, “MICROCHANNEL PLATE DETECTORS,” Nuclear Instruments and Methods, Vol. 162, 1979, p 587



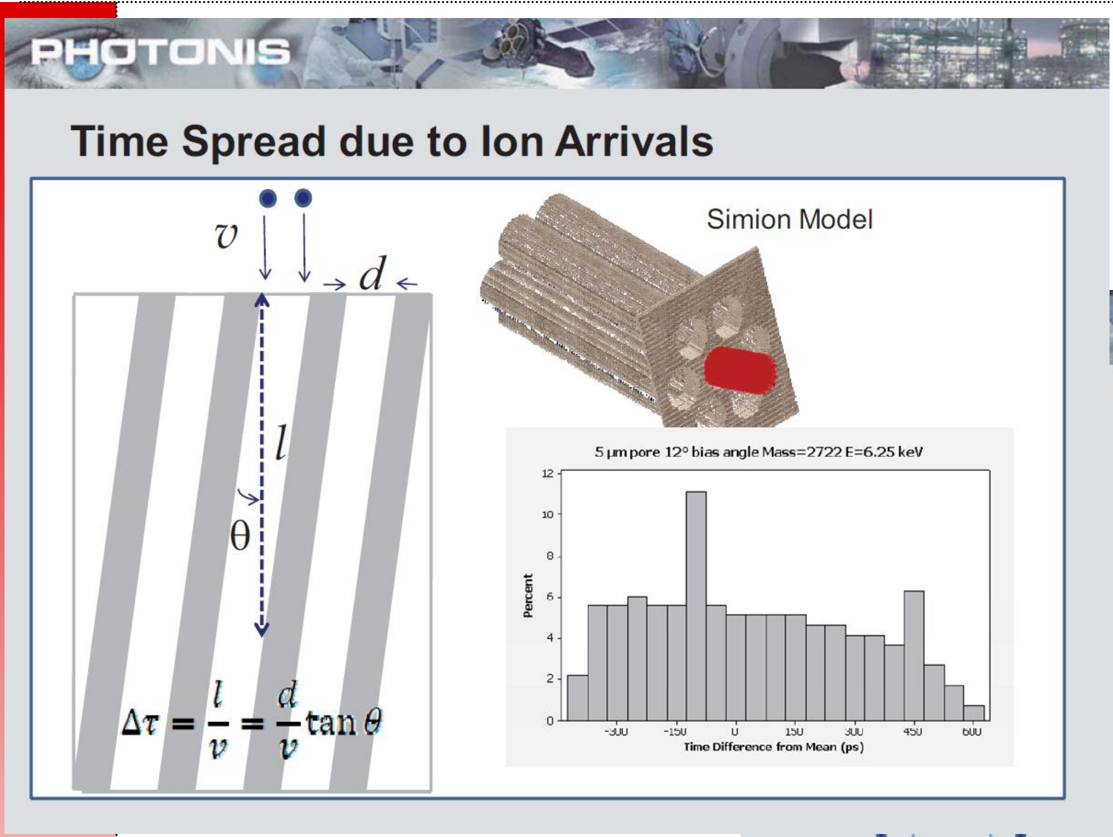
http://www.photek.com/support/ti_phd.htm





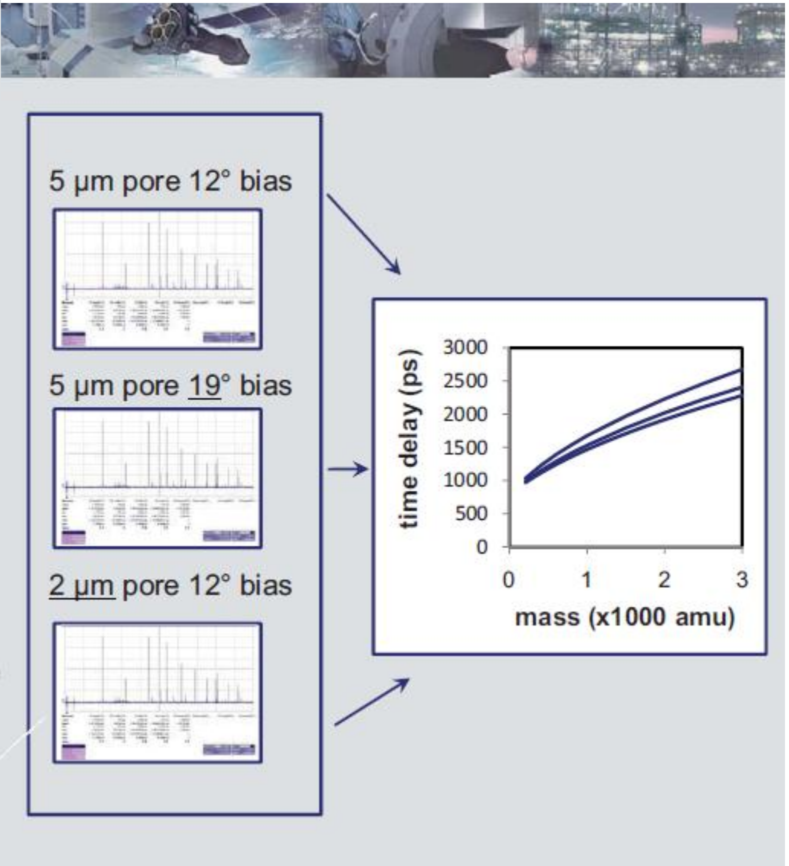


Analogue: Bias and timing for Mass Spec



Time Spread due to Ion Arrivals

$$\Delta\tau = \frac{l}{v} = \frac{d}{v}\tan\theta$$

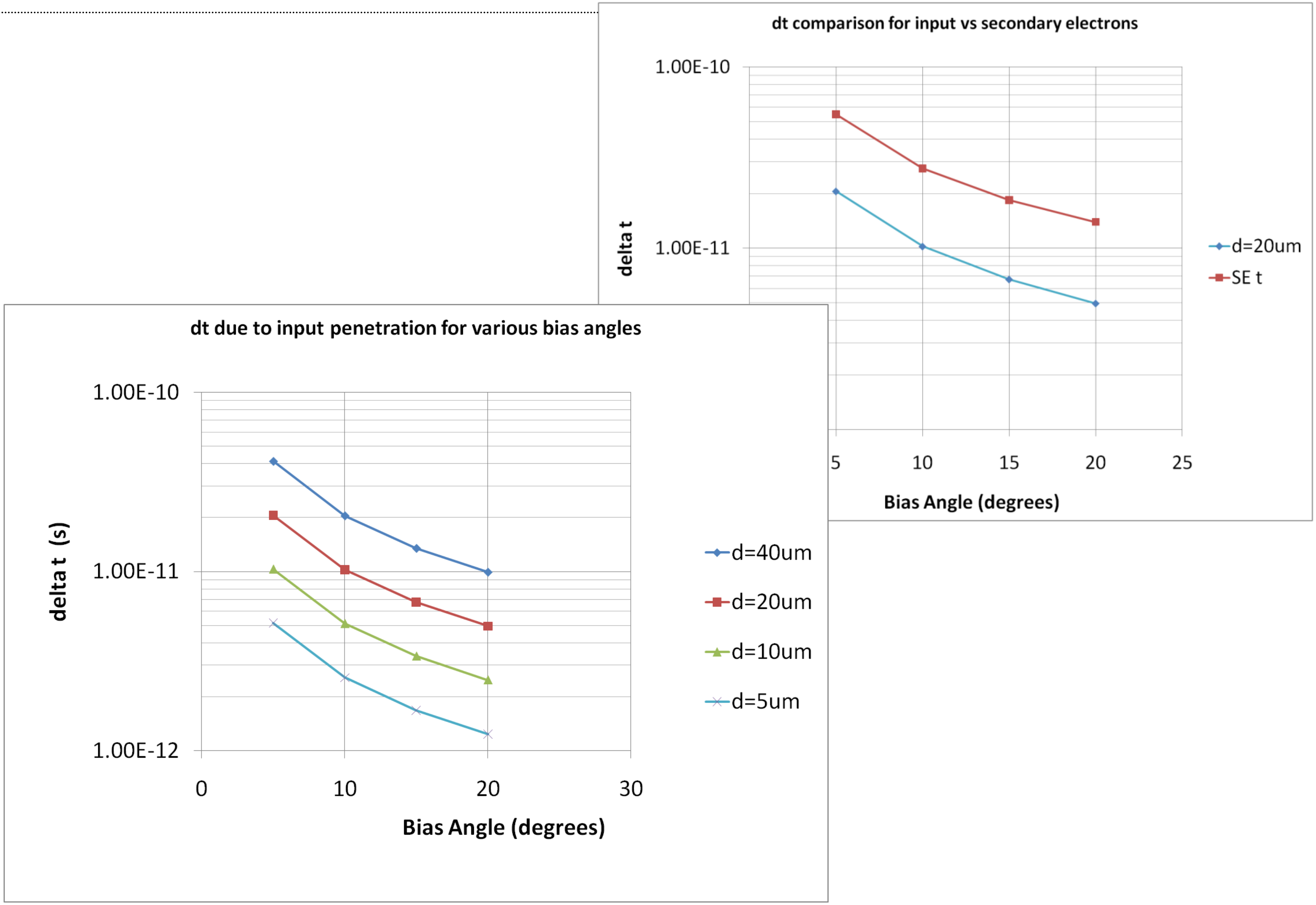


5 µm pore 12° bias

5 µm pore 19° bias

2 µm pore 12° bias

Sub 10ps – Everything Matters

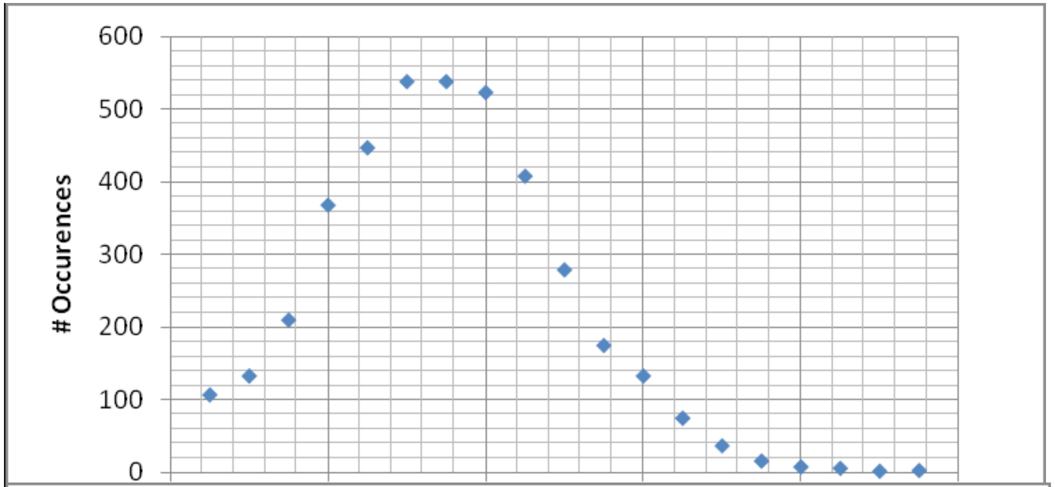


dt comparison for input vs secondary electrons

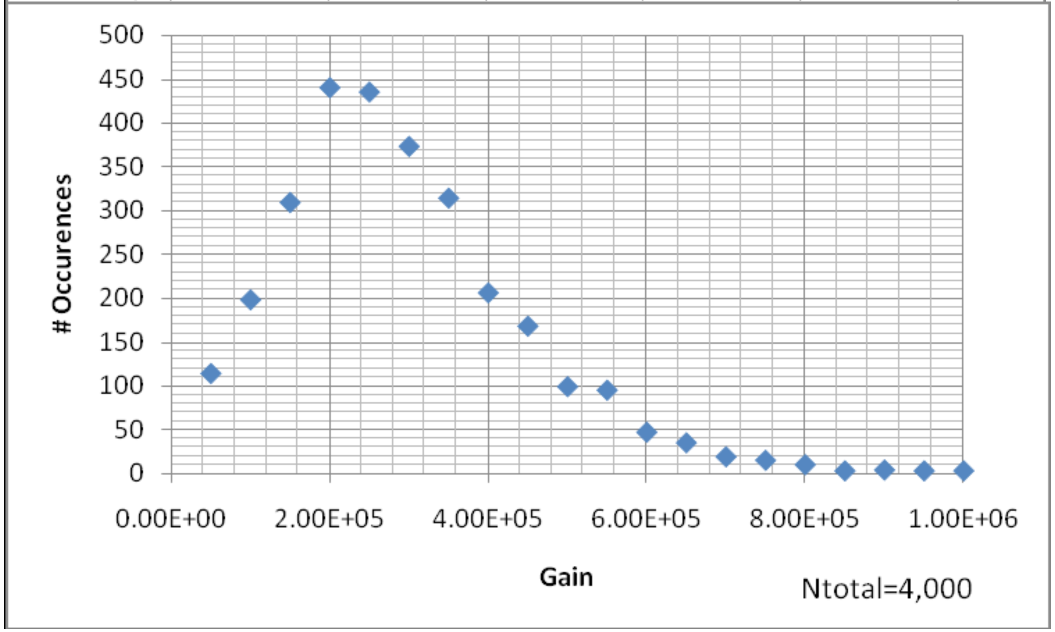
dt due to input penetration for various bias angles

PHD Negative Exponential: first strike?

- 1st Strike Fixed position

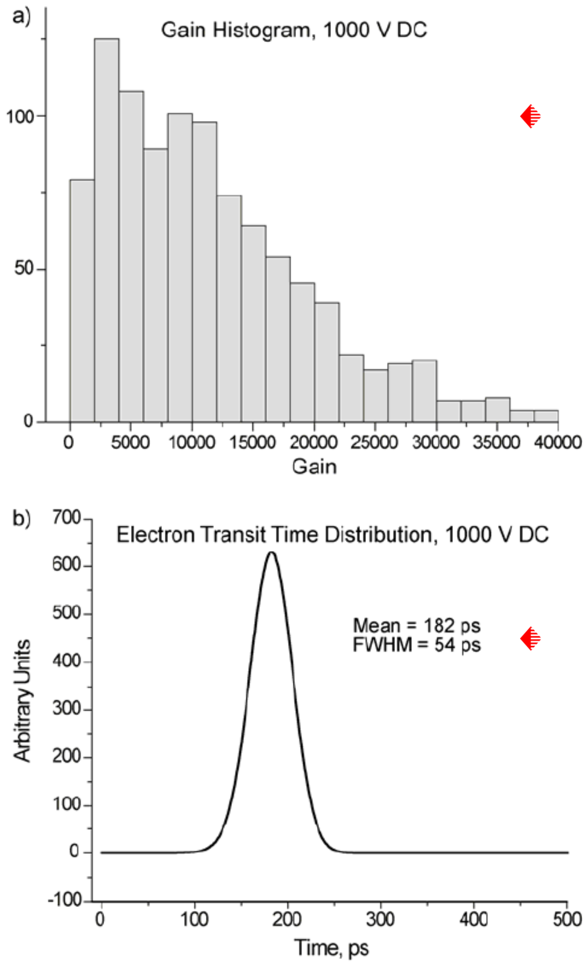


- 1st Strike Random position

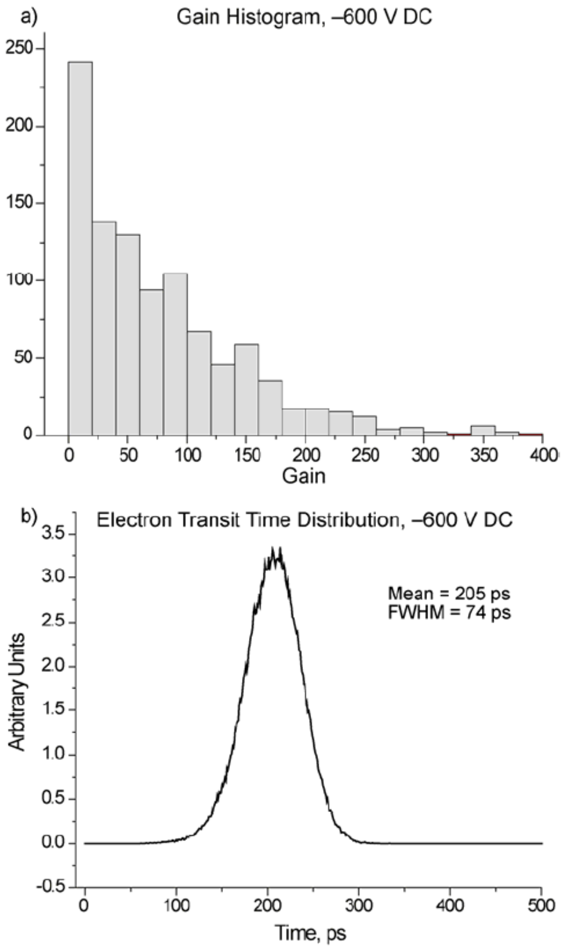


What happens when MCP Bias is reduced?

“Monte Carlo simulations of microchannel plate detectors I: steady-state voltage bias results,” M. Wu, C. Kruschwitz, D. Morgan, J. Morgan; National Security Technologies, 87544 DOE/NV/25946--400

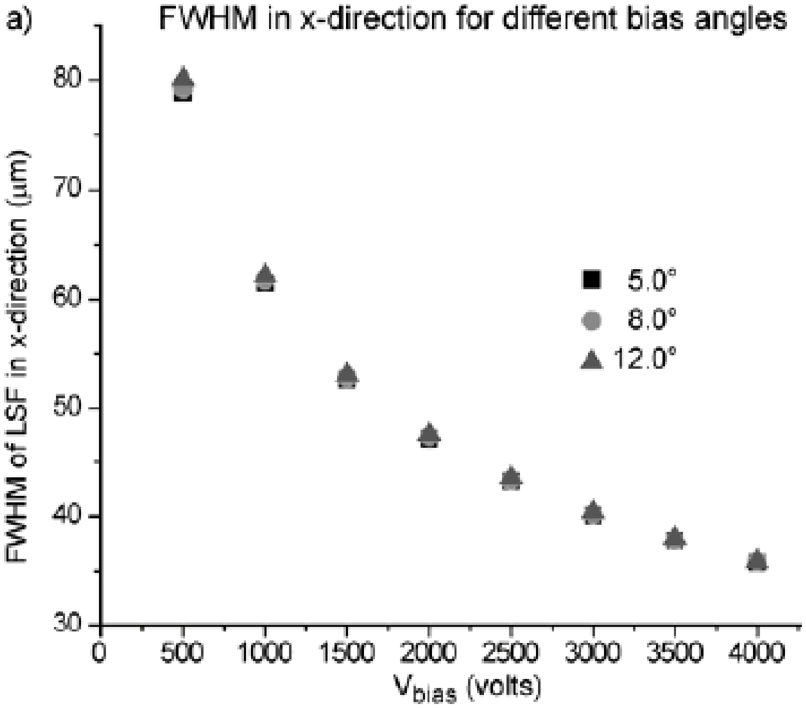


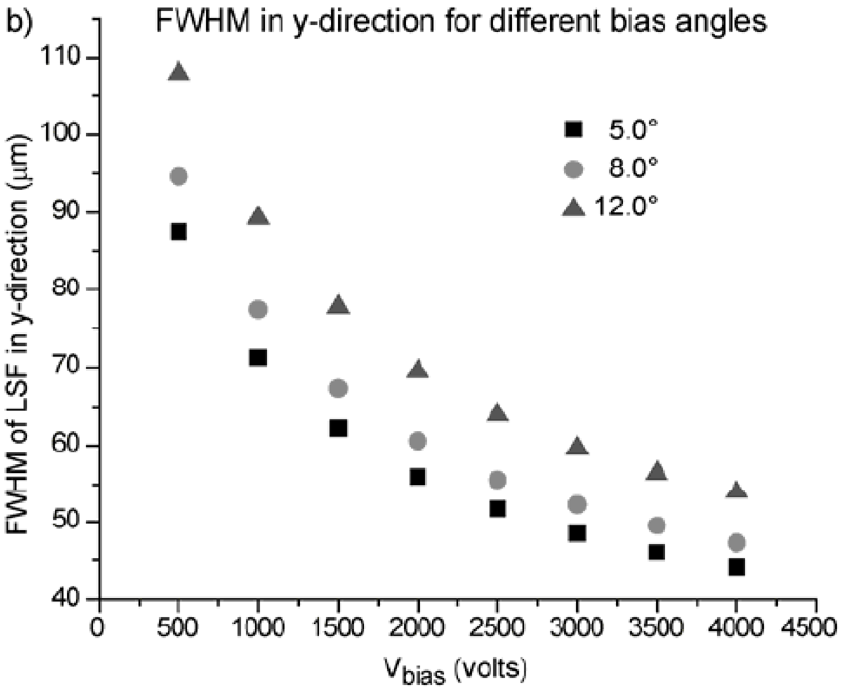
- Lower gain due to smaller electron impact energies reducing SEY.
- Mean transit time is 23ps longer at 600 V due to decreased acceleration and increased number of electron cascades. The electrons travel a shorter distance down the channel between collisions, and thus require more time to reach the output end.
- TTS for the 600 V case is 20ps larger, since the spread in SE energy and direction play a greater role at lower bias voltages: electrons travel shorter distances between collisions & impact with lower energy.



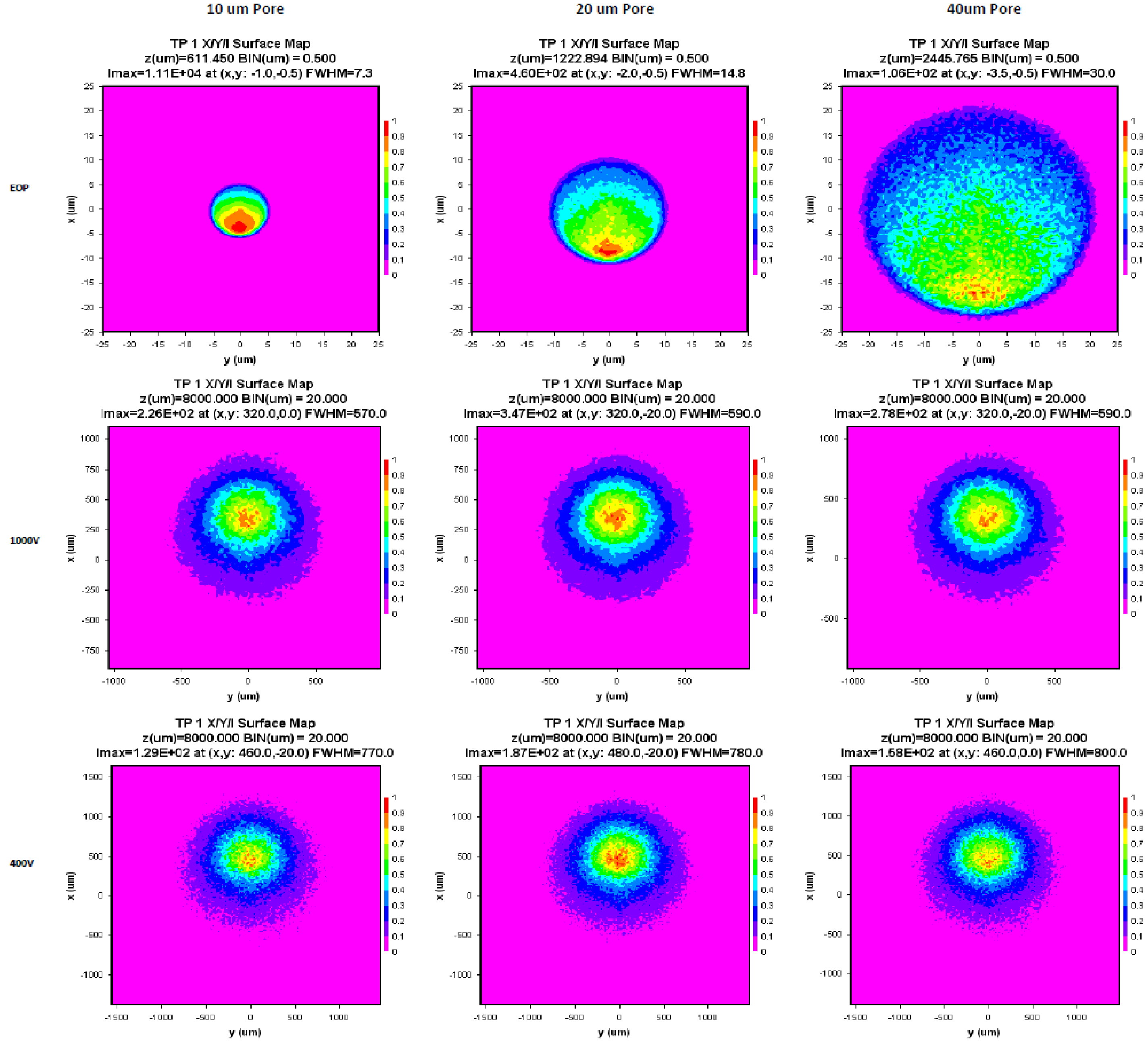
Bias angle vs. resolution

“Monte Carlo simulations of microchannel plate detectors I: steady-state voltage bias results,” M. Wu, C. Kruschwitz, D. Morgan, J. Morgan; National Security Technologies, 87544 DOE/NV/25946--400





ANDODE SPACING 8 MM



TP 1 X/Y/I Surface Map
z(um)=611.450 BIN(um) = 0.500
Imax=1.11E+04 at (x,y: -1.0,-0.5) FWHM=7.3

TP 1 X/Y/I Surface Map
z(um)=1222.894 BIN(um) = 0.500
Imax=4.60E+02 at (x,y: -2.0,-0.5) FWHM=14.8

TP 1 X/Y/I Surface Map
z(um)=2445.765 BIN(um) = 0.500
Imax=1.06E+02 at (x,y: -3.5,-0.5) FWHM=30.0

TP 1 X/Y/I Surface Map
z(um)=8000.000 BIN(um) = 20.000
Imax=2.26E+02 at (x,y: 320.0,0.0) FWHM=570.0

TP 1 X/Y/I Surface Map
z(um)=8000.000 BIN(um) = 20.000
Imax=3.47E+02 at (x,y: 320.0,-20.0) FWHM=590.0

TP 1 X/Y/I Surface Map
z(um)=8000.000 BIN(um) = 20.000
Imax=2.78E+02 at (x,y: 320.0,-20.0) FWHM=590.0

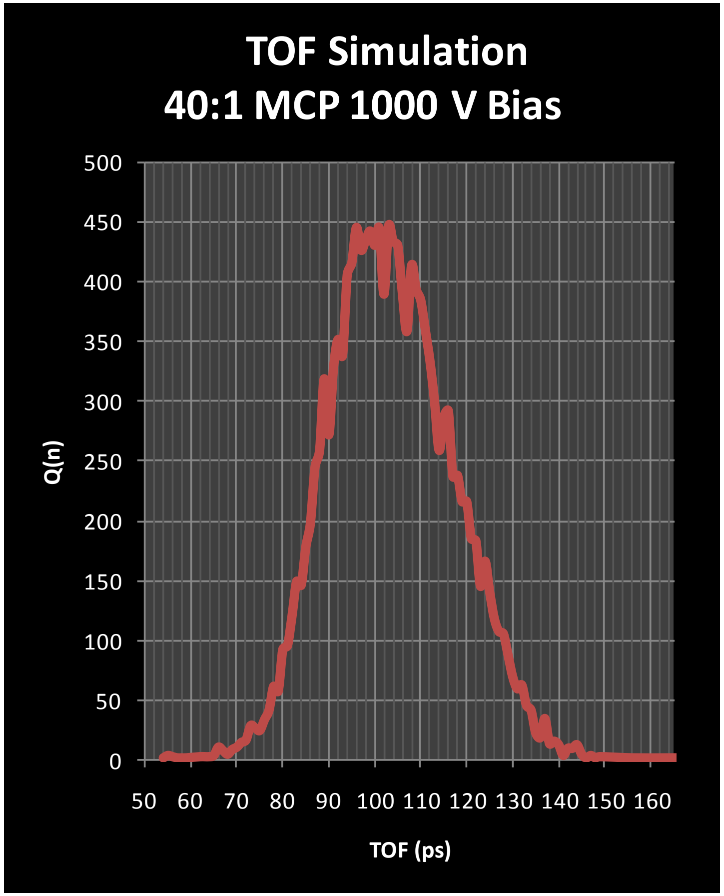
TP 1 X/Y/I Surface Map
z(um)=8000.000 BIN(um) = 20.000
Imax=1.29E+02 at (x,y: 460.0,-20.0) FWHM=770.0

TP 1 X/Y/I Surface Map
z(um)=8000.000 BIN(um) = 20.000
Imax=1.87E+02 at (x,y: 480.0,-20.0) FWHM=780.0

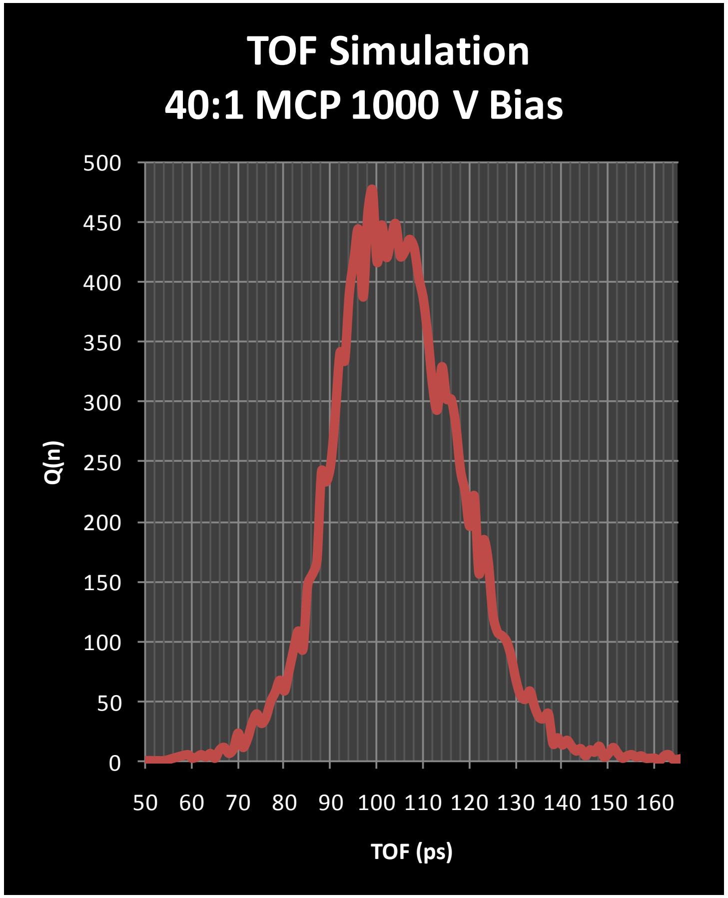
TP 1 X/Y/I Surface Map
z(um)=8000.000 BIN(um) = 20.000
Imax=1.58E+02 at (x,y: 460.0,0.0) FWHM=800.0

MCP CASCADE TOF Comparison –Pore Exit

Low Yield ES



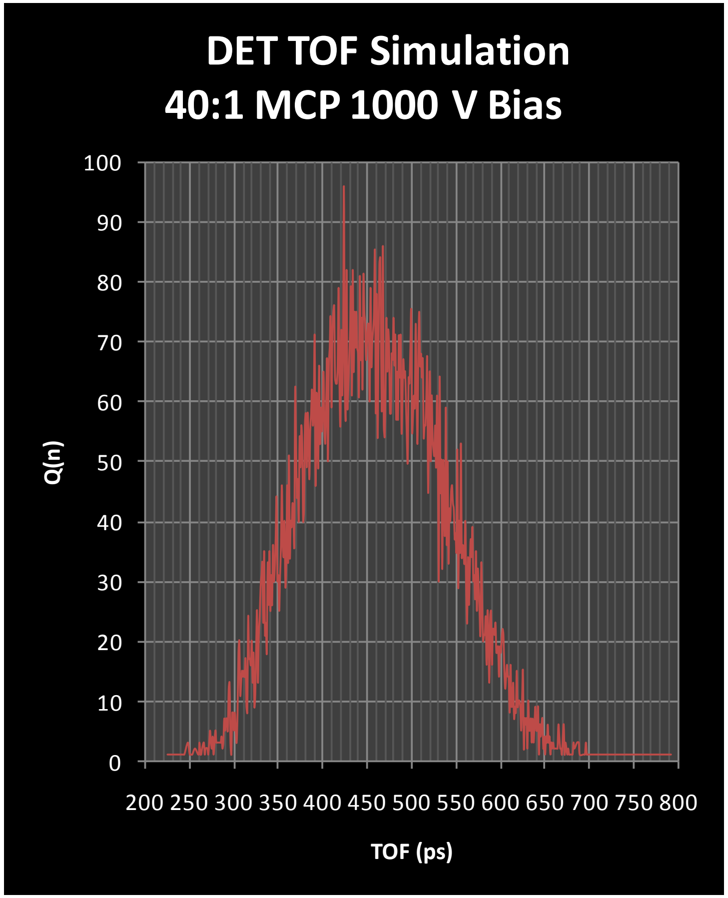
High Yield ES



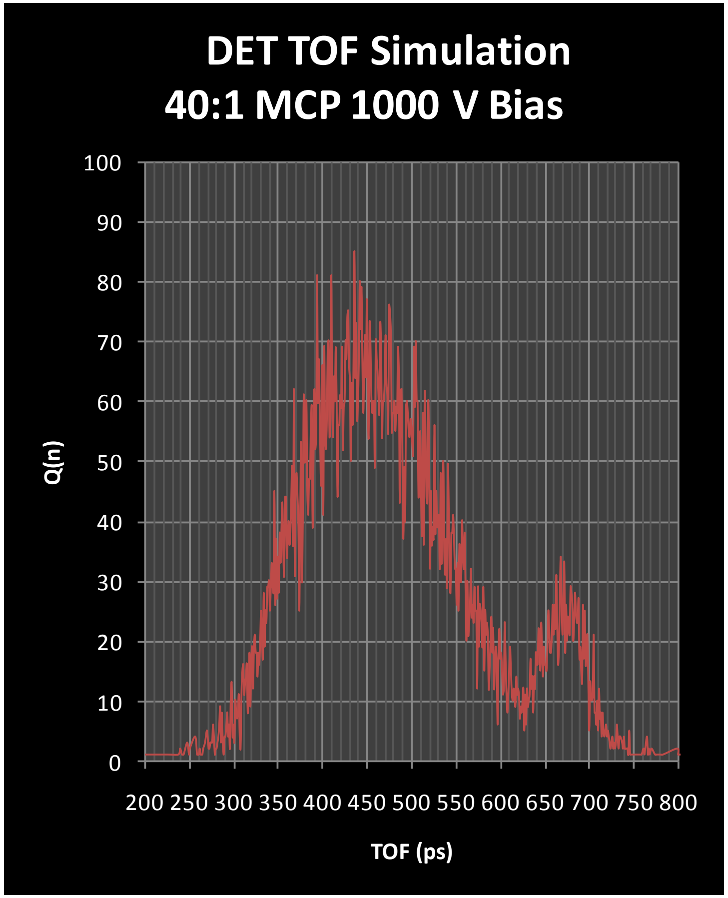
At the EOF the SE yield of the ES material has little influence on TOF

MCP CASCADE TOF Comparison – Detector

Low Yield ES

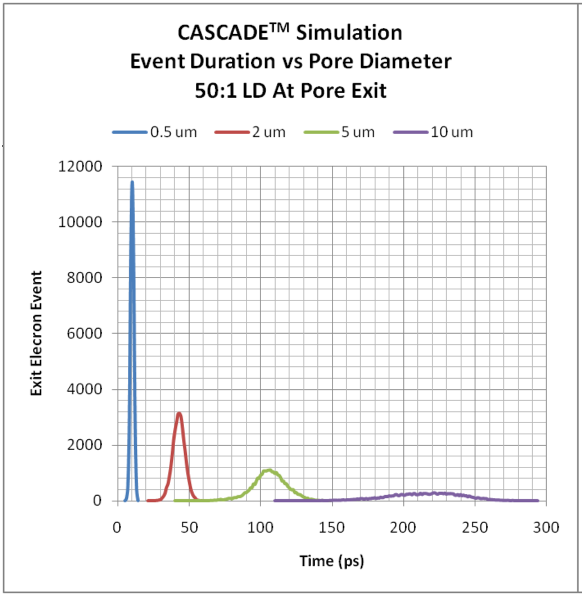


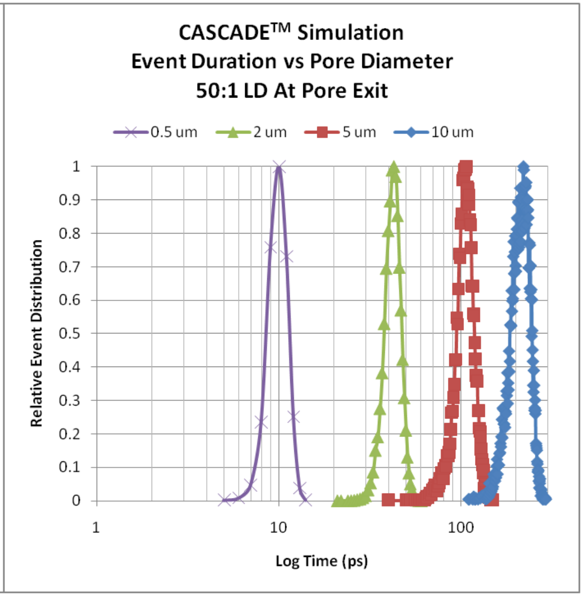
High Yield ES



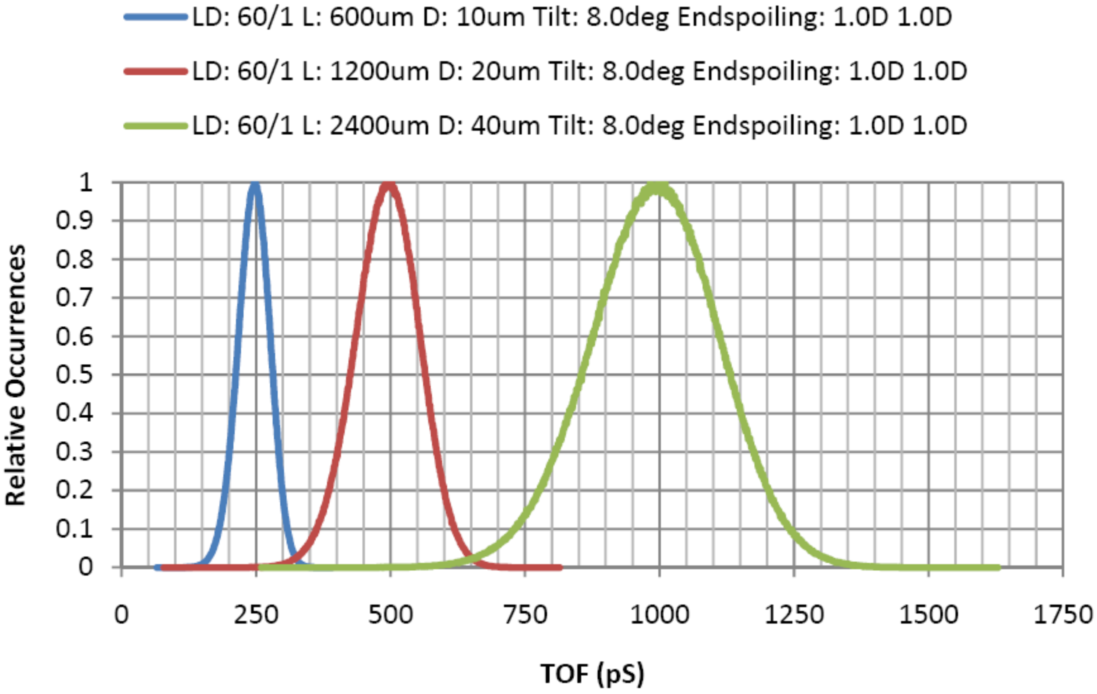
At the Detector the SE yield of the ES material has a significant influence on TOF. The increased low eV electrons will extend the TOF distribution to the detector. In this extreme example, a second peak can be observed for the high yield material.

MCP CASCADE: MTT & TTS





CASCADE TOF
Event Start to EOP
1000V

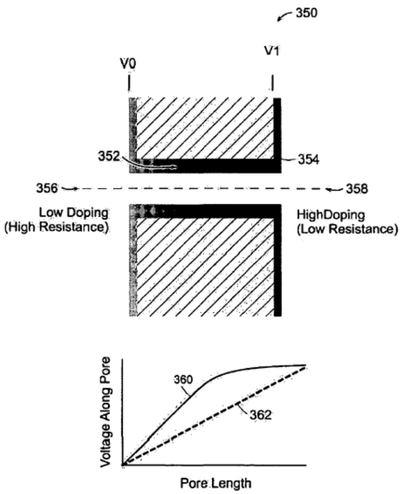


Why TTS a consistent fraction of MTT?

TTS Questions – Film properties

- What is the impact of SEY on TTS (effect of gain)
  - more is better?
  - Is there an optimum?
  - Does first strike (high or low) make a difference?
- Does bandwidth (e.g. resistance) make a difference?
- What happens if you tailor the pore nanofilm properties

  – USP **7408142**



TTS Questions – MCP Geometry

- What is the optimal pore size, OAR, input funneling, L:D, bias angle for all of the other tradeoffs: gain, spatial resolution, timing resolution
- What is the role of endspoiling?
- What is the role of Substrate non-flatness?
- Can such a fully optimized substrate be made more than once?
- What does saturation do to TTS?
- What does gain do to TTS?

TTS Questions – MCP-PMT device

- What is the optimal interplate gap?
- What is the optimal bias angle for plate 1? Plate 2?
- What is the optimal pore size for plate 1? Plate 2?
- Is there advantage to a single, very high gain MCP? How does this optimization compare to the MCP geometry optimization?