SWEATERS Project
Advances in Simulating the Operating Principles of Micromegas at Low Pressures

Status Report for DRD1 Collaboration Meeting – WG4

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Micromegas in SWEATERS Project and MC software baseline

SWEATERS (Space Weather Ena Radiation Sensors) project

SWEATERS is focused on the detection of Energetic Neutral Atoms (ENA) in space and plans to use MPGD operating at low-pressure (75-100mb) for detection, spectrometry, and imaging of low energy atom (H, O @ 1-100KeV).

Why MPGD at low pressures?

- to use, in vacuum space, ultrathin inlet window for ENA – Ion conversion AND to increase ions track length

Test bench

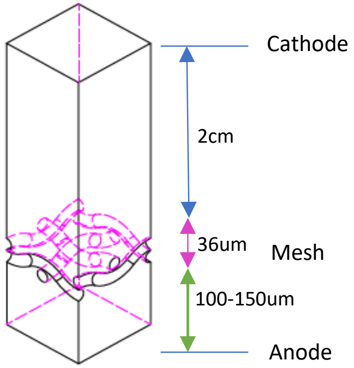
- MM192 [150 µm effective], Ar 93% CO2 7%, pressures NTP, 75-150mbar, Sources: Fe55 X-Ray (5.9KeV), H+/He+ beams (1-5KeV)

Why MC Simulations?

- to predict the gain with different avalanche gaps (150-500 µm), mix, pressure & to identify the physical processes which affect stability

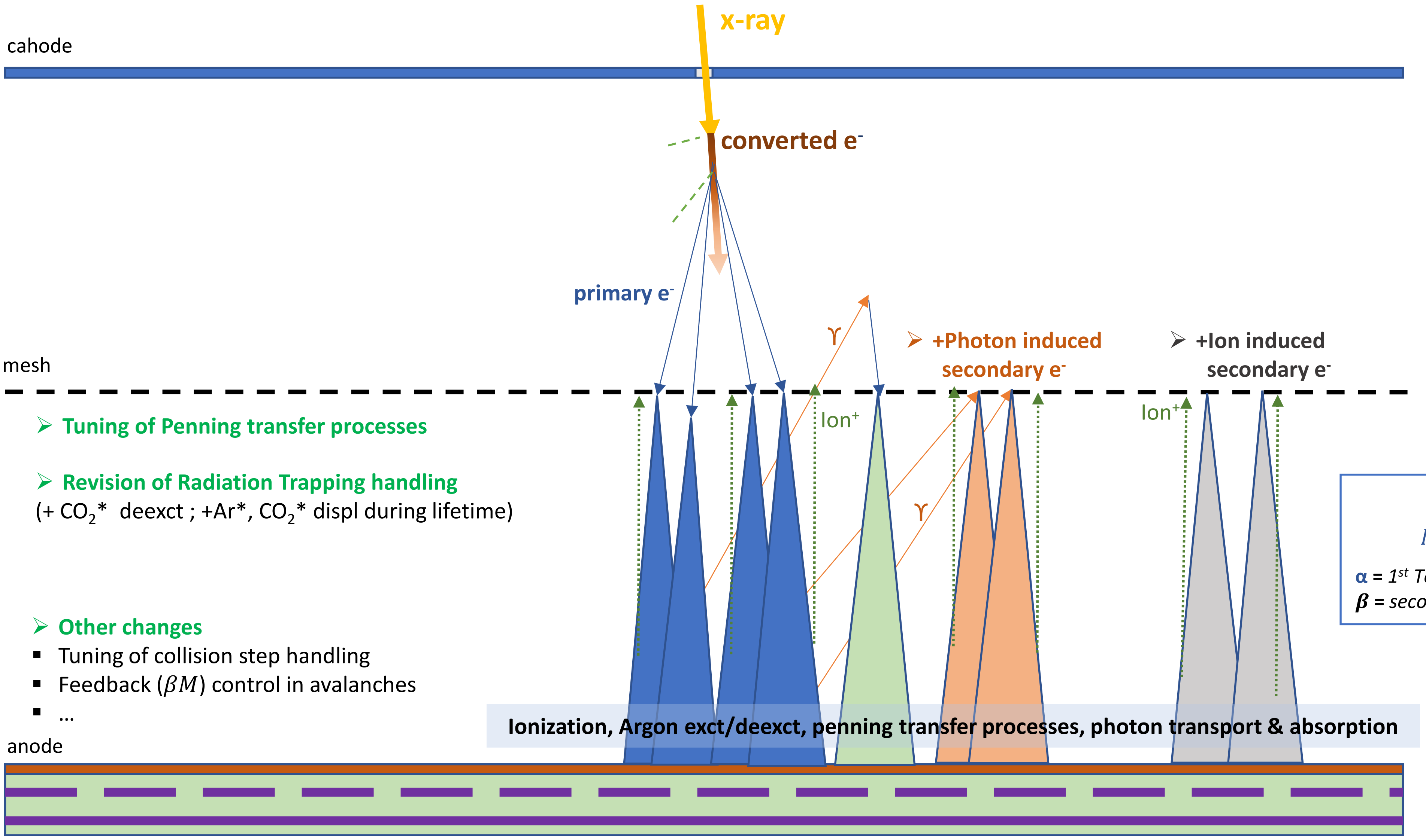
MC software baseline

- **Drift**:
  - Geant4 framework (fast simulators)
  - Degrad for x-rays test bench
  - SRIM for ion beam test bench
  - Garfield++ for electron drift
- **Avalanche**:
  - **Garfield++**
  - Ansys



More details on Sweaters in [1] G.Antonelli, [2] A.Foresi et al. and [3] F.Pilo et al.

Overview of add-ons and changes to Garfield++



- **Tuning of Penning transfer processes**

- **Revision of Radiation Trapping handling**

(+ CO_2* deexct ; +Ar*, CO_2* displ during lifetime)

- **Other changes**
  - Tuning of collision step handling
  - Feedback (βM) control in avalanches
  - …

Multiplication factor

$$M = e^{\alpha d} \Rightarrow M_T = \frac{M}{1-\beta M}$$

α = 1st *Townsend coeff*

β = *secondary aval. per aval. e el/ion*

Photons handling and photon induced secondary emissions

A) Deexcitation handling

- Use detailed Ar* deexcitation code in Garfield++ (not the Penning transfer rate mode) => Tuning of penning transfer processes in Garfield++
- + handling of CO_2^{+*} deexcitation $B\,^2\Sigma_u^+ \rightarrow X\,^2\Pi_g$ at 5.66 eV based on *[6] Y.Itikawa* (just to “scrape the barrel”)
- + displacement of excited states during lifetime (may be up to 1 µm)

B) Photoabsorption

- ϒ -> CO2: photoabsorption cross section (OpticalData)
- ϒ -> Argon: photoabsorption cross section (OpticalData) + **discrete line absorption** => Radiation trapping

C1) Photoionization generating new avalanches

- At our low pressure and gap, photoionization may occur even up to the drift region (OpticalData)

C2) Photoelectric emission at mesh surface generating new avalanches

- + photon-mesh interaction in photon transport
- Photoelectric emission: $E_{\Upsilon} > 5$ eV (Nickel work function), e- energy : $E_e = E_{\Upsilon} - 5$
- Nickel yield from *[4] R. B. Cairns and J. A. R. Samson*

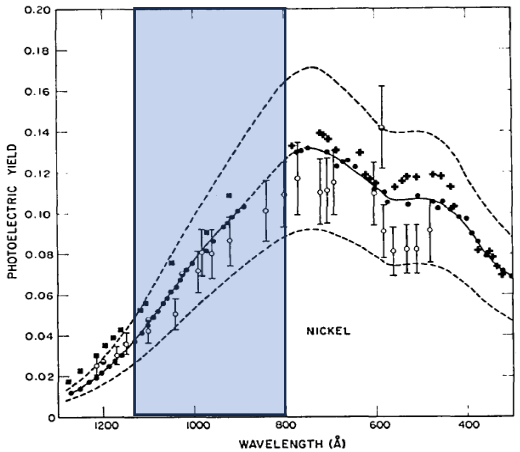


FIG. 3. Photoelectric yield of nickel: ● present data, + present data (second sample), ◐ data of Hinteregger and Watanabe,[9] ■ data of Watanabe *et al.*,[11] ---- curves representing the present data ±30%, ○ data of Walker *et al.*[10]

Yield strongly depends also on surface status *[5] W.C.Walker et al.*

No angular distribution of photons is applied. The surface status of our mesh is rather indeterminate.

Tuning of penning transfer processes in Garfield++

Which r_{Pen} @ NTP?

[11] O.Sahin Penning transfer rate r_{Pen} : $\alpha_{Pen} = \alpha\left(1+\frac{\sum r_{Pen}\nu_i^{exc}}{\sum \nu_{mix}^{ion}}\right) \approx \alpha_{Pen} := \alpha\left(1 + r_{Pen}\frac{f^{exc}}{f^{ion}}\right),$ $r_{Pen} = r_{Pen}(press, \%CO_2) \Rightarrow r_{Pen}(1\ atm, 7\%) = 0.38$

Tuning of Argon deexcitation processes leading to penning transfer processes to have **r_{Pen}** = 0.38 at NTP, CO_2 7% and also to match variations with 6%, 8%.

The parameters which we found had to be tuned were the rate constants of the homonuclear associative ionization: $Ar^* + Ar \rightarrow Ar_2^+ + e^-$

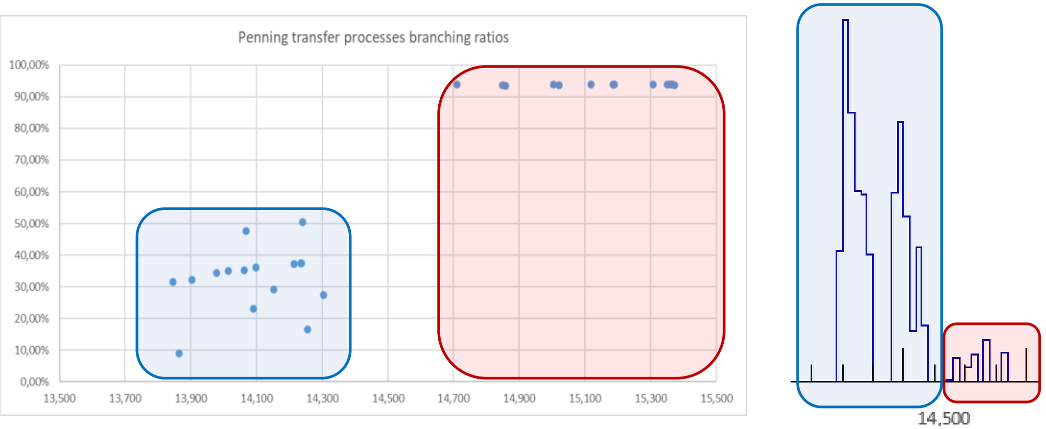
- Transfer to 4p levels *k4p:* *1.e-20 => 6.5e-20*
- Hornbeck-Molnar ionization *kHM:* *2.e-18 => 1.e-18*

Which r_{Pen} @ low pressures with the above setting?

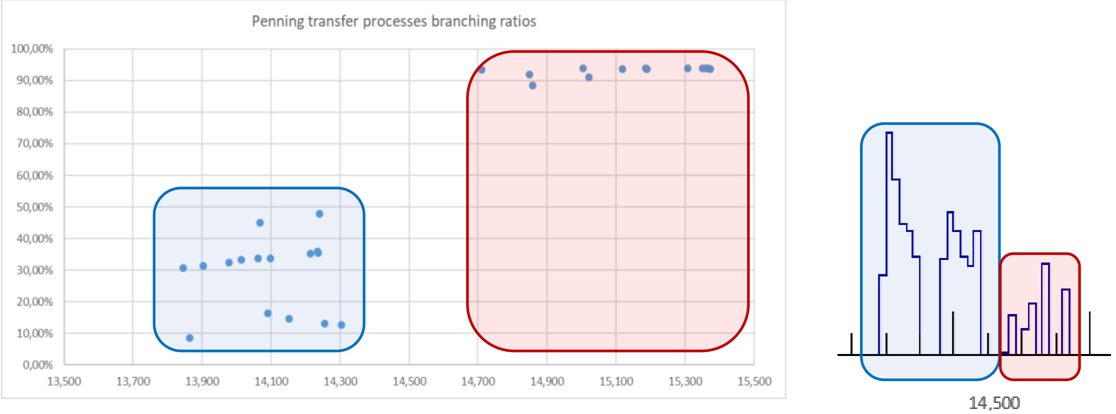
@ 75-150mb $r_{Pen}(p, c) \approx 0.20$ but from MC **r_{Pen}** ≈ 0.44 , why?

r_{Pen} depends also on E/p: at lower p energy of e- at collisions grows so that Ar excited states tend to be more populated towards higher energy states which have higher BR

BR and excited state population at NTP



BR and excited state population at 100mb



Tuning could be improved by trying to adapt better to intermediate pressures.

Radiation trapping

A) Excited states: Magboltz cross sections

e- + Ar -> Ar* + e-

B) Radiative deexcitations: Argon specific handling in Garfield++

Ar* -> Ar + ϒ E_Υ = initial exc state energy + RndmVoigt(0., sDoppler, gPressure)

Ar** -> Ar* + ϒ E_Υ = initial exc state energy – final exc state energy

C) ϒ collision frequencies: continuum & discrete line absorption

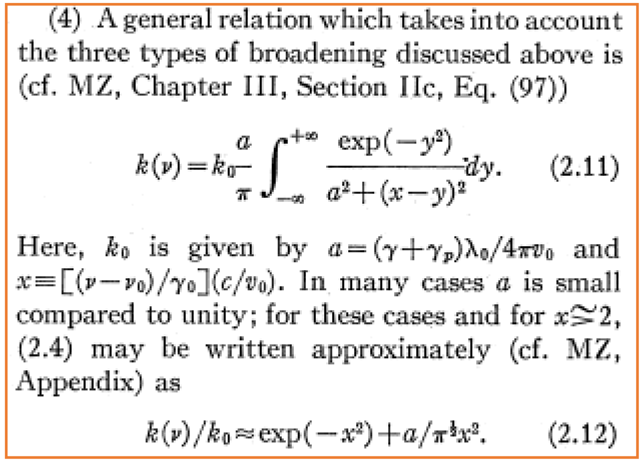
$cf_\Upsilon = cf_{cont} + cf_{disc}$

cf_{cont} from OpticalData $[=n^{Ar}\, c\, \sigma^{Ar}_{abs}\, (1-\Upsilon^{Ar}_{ion}) + n^{CO2}\, c\, \sigma^{CO2}_{abs}\, (1-\Upsilon^{CO2}_{ion})]$

cf_{disc} ??? from radiation absorption coefficient K(v) calculated in *[7] T.Holstein*

$cf_{disc} = \sigma_{disc}(v)*c*\, n^{Ar}$, $\sigma_{disc}(v) = K(v) / n^{Ar}$ => $cf_{disc} = K(v)*c$

T.Holstein - Imprisonment of Resonance Radiation in Gases
Phys. Rev. 72, 1212 – 1947



(4) A general relation which takes into account the three types of broadening discussed above is (cf. MZ, Chapter III, Section IIc, Eq. (97))

$$k(\nu)=k_0\frac{a}{\pi}\int_{-\infty}^{+\infty}\frac{\exp(-y^2)}{a^2+(x-y)^2}dy. \qquad (2.11)$$

Here, k_0 is given by $a=(\gamma+\gamma_p)\lambda_0/4\pi v_0$ and $x\equiv[(\nu-\nu_0)/\gamma_0](c/v_0)$. In many cases a is small compared to unity; for these cases and for $x\gtrsim 2$, (2.4) may be written approximately (cf. MZ, Appendix) as

$$k(\nu)/k_0\approx\exp(-x^2)+a/\pi^{\frac{1}{2}}x^2. \qquad (2.12)$$

As expected, cf_{disc} is extremely high (5/6 orders of magnitude cf_{cont}) => we apply two constraints lo limit the resulting % of photons absorbed

1) $cf_\Upsilon < n^{Ar}\, c\, \pi r_{Ar}^2$

2) $cf_\Upsilon = cf_{cont} + cf_{disc}$ if $E_\Upsilon <$ **X** * fwhmVoigt(E_Υ) ; cf = cf_{cont} otherwise

@NTP, 500mb, 150mb **X = 6** (99.6% cf_{cont} + cf_{disc} ; 0.4% cf_{cont})

@100mb **X = 4** (99.4% cf_{cont} + cf_{disc} ; 0.6% cf_{cont})

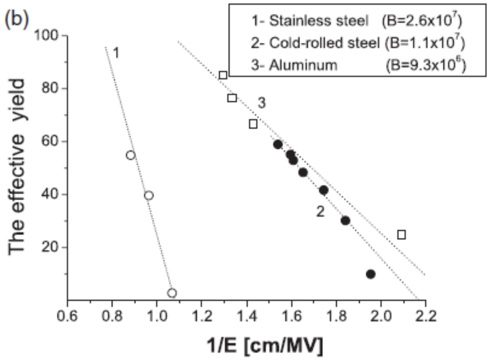
@75mb **X = 1** (97.4% cf_{cont} + cf_{disc} ; 2.6% cf_{cont})

This part need to be improved to have the right dependency of CF on the pressure without the need for adjustments

Ion induced secondary emission on mesh

Photoelectric emissions cannot fully account for our gains: **can ions reaching the mesh trigger secondary electron emission?**
We added ion transport in AvalancheMicroscopic to investigate two models *[8] K.T.A.L. Burm* and *[9] M. Klas.*
[9] M.Klas on **ion enhanced field emission** works best in our context. It deals with a discharge system consisting of two parallel planar Cu electrodes at separations from 20 to 500 μm. Here yield depends on electric field, ion energy and metal and is tested at various E/p.

Yield vs Electric Field

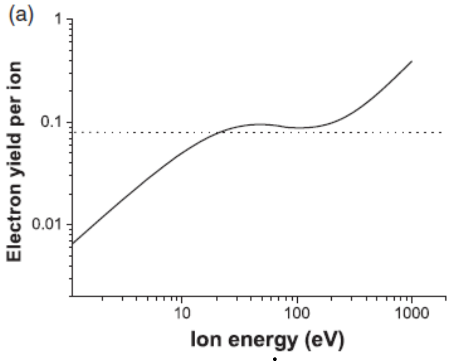


Our case

Garfield (Ansys): 40kV/cm … 85kV/cm on mesh
What are true E on mesh and yield for Nickel?
[9] M.Klas works at discharge conditions

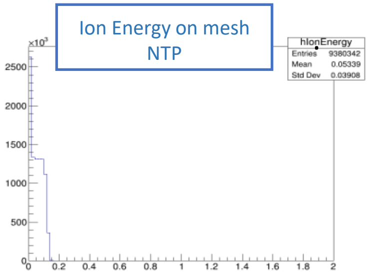
=> threshold on E field at mesh > 30kV/cm

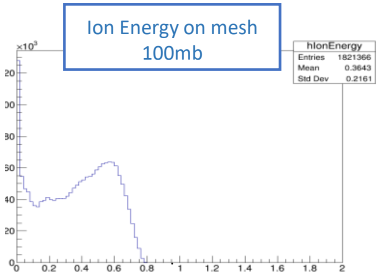
Yield vs Ion Energy



Yield strongly depends also on surface status *[10] R.Buschhaus et al.*

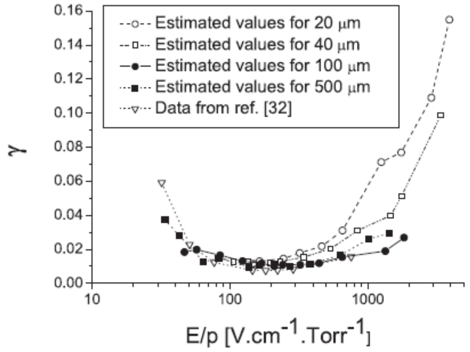
Our case





=> yield from (a) & threshold on ions energy at mesh > 0.5 eV

Yield vs E/p



Our case

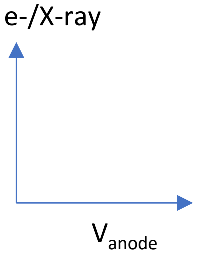
@ 75-150mbar: E/p ≈ 200-300 V cm-1 Torr-1

=> same setting for all E/P

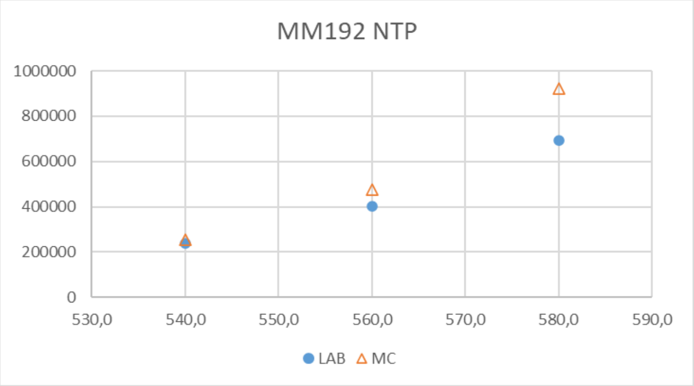
Our model is mostly derived from iterative tuning to match measurements: further validation is needed. The surface status of our mesh is rather indeterminate.

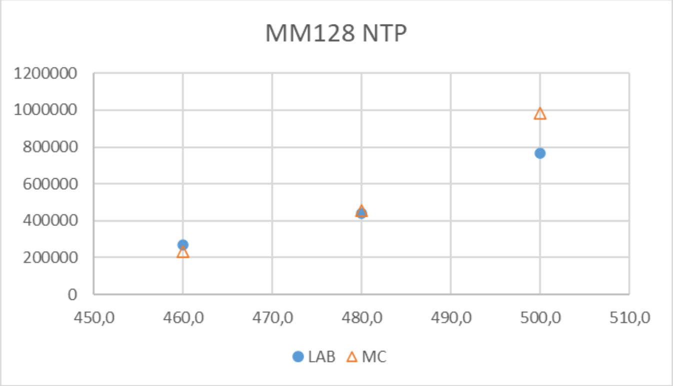
MC vs laboratory measures 1/2

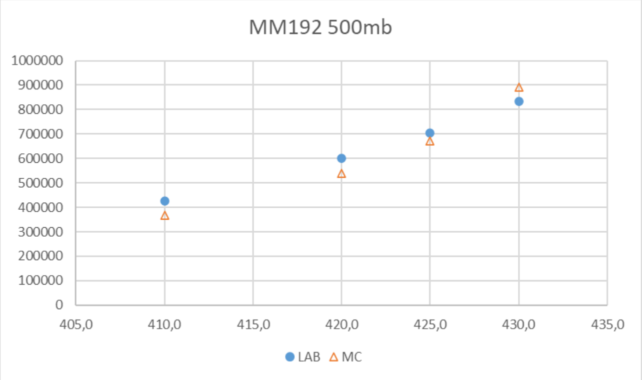
> Overall gain

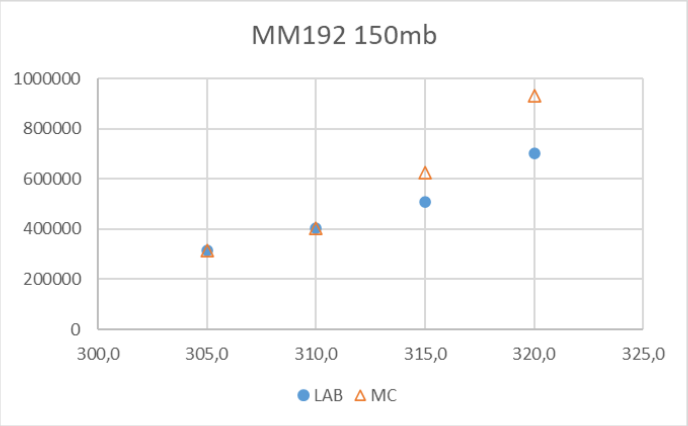


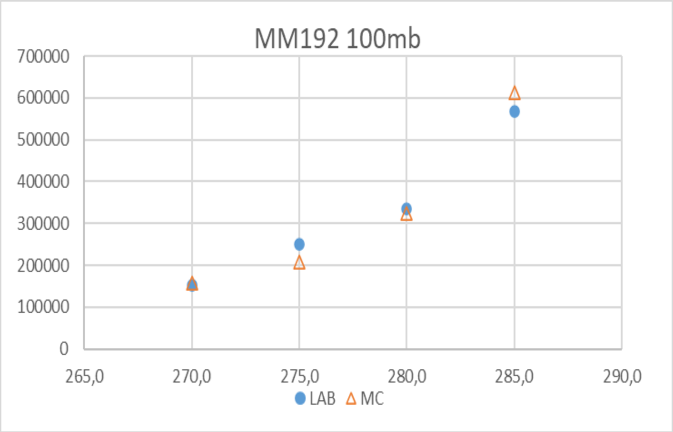
$M_T \approx$ (e-/X-ray)/210e-

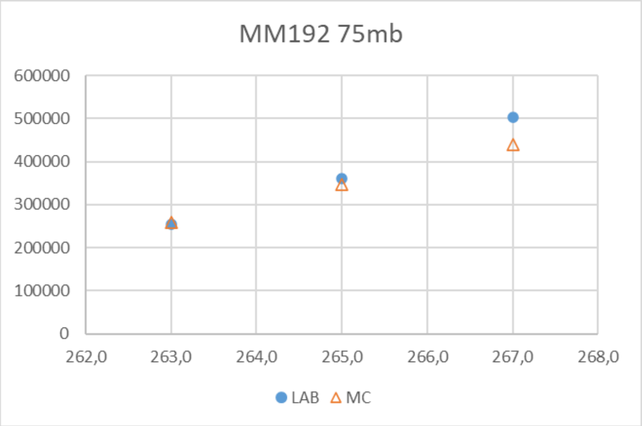






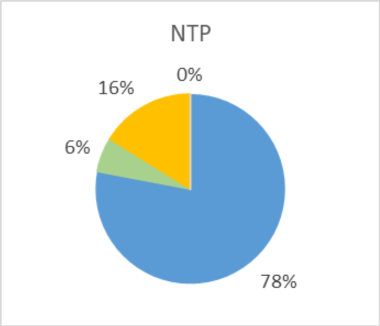


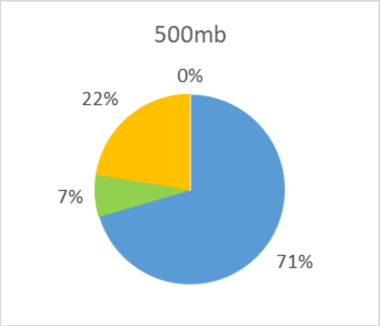


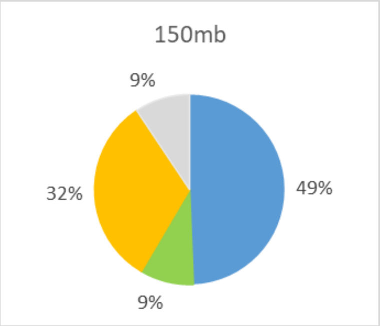


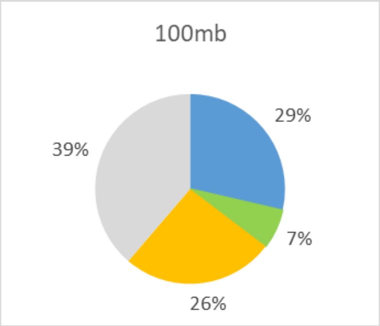
> Aval origin

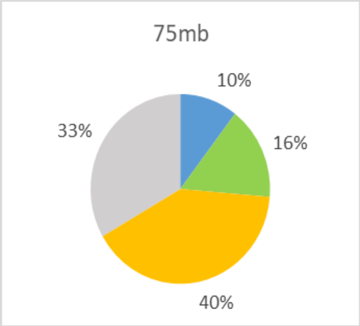
Avalanche Origin
Primary
Υ-drift
Υ-mesh
ion-mesh





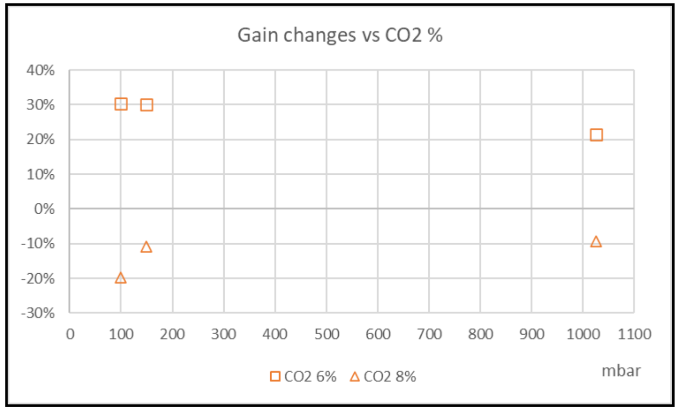




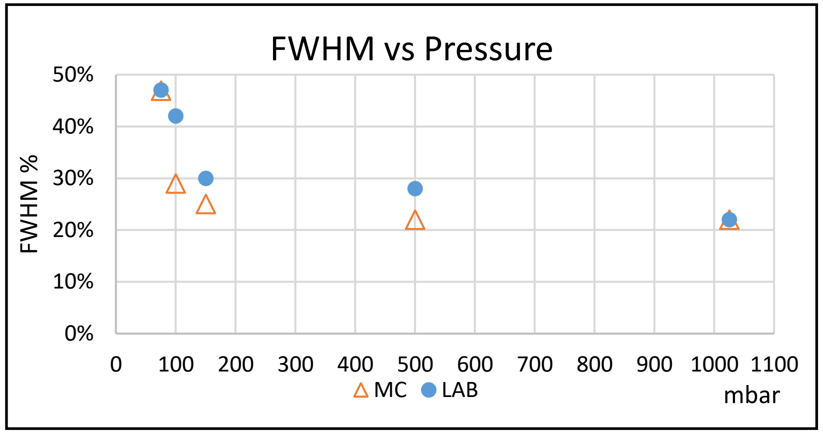


MC vs laboratory measures 2/2

> Gain changes vs CO2 % (CO2 7% => 0%)



> FWHM of e-/x-ray vs Pressure



> Changes in working point after MM reassembling: we observe same gains at lower V_{anode} and in narrower V ranges.

As from the following studies, if the mesh gets dirtier the yields of both secondary effects increase and so does the gain.

Yield of photoelectric emissions vs surface status
[5] W.C.Walker et al.

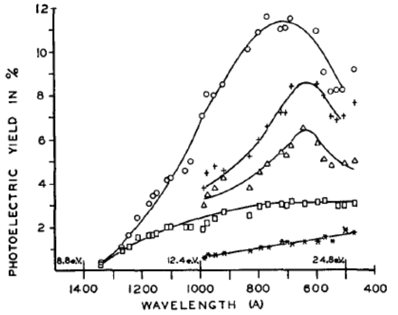
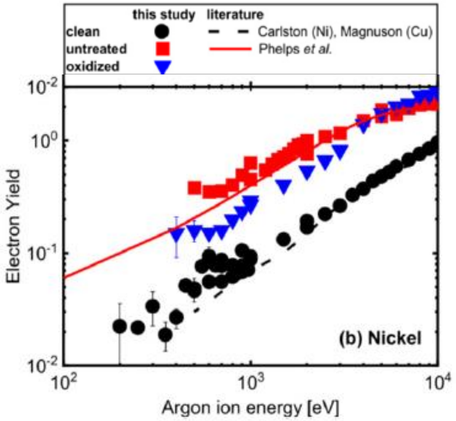


Fig. 2. Photoelectric yield of Ni. ○ Untreated cathode. □ Heat treated cathode in equilibrium with residual gases at about 10^{-5} mm Hg. * Cathode maintained at 900°C in a vacuum of 10^{-5} mm Hg. △ Heat treated cathode at room temperature after exposure to O_2 at 0.1 mm Hg for one-half hour. + Heat treated cathode. heated in 0.05 mm Hg of O_2 at 800°C for one minute.

Yield of ion induced secondary emissions vs surface status
[10] R.Buschhaus et al.



How good our simulation model is?

- ✓ **Good agreement between measures and simulations over a wide range of pressures: 75mb – 1025mb**
- ✓ **Good agreement on gain vs CO2%: it increases with less CO2 %**
- ✓ **Good agreement on energy resolution (fwhm)**
- ✓ **Can explain changes in working point after MM reassembling.**

- ☐ **It still needs adjustment on absorption of discrete lines under 100mbar**
- ☐ **Ion induced secondary emissions needs some independent validation**
- ☐ **Resulting Penning transfer rate vs pressure, compared to literature, should be refined**

- ➢ **Predictions with forthcoming MM with larger gaps will be a good test of the model**
- ➢ **Predictions on the rise time of the signals on the mesh and predictions on the footprint of the avalanches on strips could be another validation test, if we'll be able to make measurements with enough accuracy**
- ➢ **Predictions on changes due to the condition of mesh surface, if we we'll be able to set-up specific tests**

We emphasize that **these are simulations** where various processes are interconnected and concur in the same or opposite direction, difficult to discriminate.

List of major actions on Garfield++

A. **Collision steps handling**
   - Enabled Null Collision Steps to update electron energy on null collisions
   - Increased Null Collision frequency at lower pressures (e- mean free path is ~ 0.3/2.7/4.8 um @NTP/100/50mbar)

B. **Detailed deexcitation mode**
   - Use of detailed deexcitation mode instead of Penning transfer rate mode
   - Tuning of some rate constants
   - Added deexcitation of $CO2^{+*}$
   - Added displacement of excited states during lifetime

C. **Radiation Trapping**
   - Review of how broadening is used in discrete line emissions
   - Calculation of collision frequencies for discrete lines absorption, based on Holstein absorption coefficient
   - Constraints on collision frequencies

D. **Photoelectric induced secondary electrons**
   - Use of photon transport
   - New code to handle photons hitting the mesh (as Ansys medium) so generating secondary electrons

E. **Ion induced secondary electrons**
   - New code to add TransportMC in AvalancheMicroscopic
   - New code to handle ions hitting the mesh (as Ansys medium) so generating secondary electrons
   - Extended range of IonMobility_Ar+_Ar.txt file
   - Changed the scaling in Ion Velocity calculation (now fixed in Garfield)

F. **Breakdown handling**
   - Dynamic calculation of βM to control avalanche growth and prevent program hanging (discharges)
   - Flagging of electrons according to the origin of the avalanche to which they belong to: primary, photon induced, drift photoionization, ion induced.

Conclusions

We'd greatly appreciate help on

a) Modelling ion induced secondary emissions

b) Modelling discrete line absorption collision frequencies

c) Other attempts to tune Penning transfer processes with Garfield++

d) Any other physical process which might be relevant at low pressures

Nice to have in Garfield++

a) Handling of gas deexcitations based on a general deexcitation model + (xml?) deexcitation data

b) Bult-in ion transport in AvalancheMicroscopic

c) Callback functions called when e-, ions, photons cross the boundaries of the medium

References

Sweaters

[1] G.Antonelli - MC Simulations of Micromegas at Low Pressure - RD51 MiniWeek - 28-29 February 2023

[2] A.Foresi et al. - X-ray characterization of a bulk resistive MICROMEGAS operating at low gas pressure
NIMA Volume 1065, August 2024, 169494 https://doi.org/10.1016/j.nima.2024.169494

[3] F.Pilo et al. - The operational principles of MICROMEGAS gas detectors at low pressure: A comprehensive exploration
NIMA Volume 1070, Part 1, January 2025, 170011 https://doi.org/10.1016/j.nima.2024.170011

Photoelectric emissions

[4] R. B. Cairns and J. A. R. Samson - Metal Photocathodes as Secondary Standards for Absolute Intensity Measurements in the Vacuum Ultraviolet
Journal of the Optical Society of America Vol. 56, Issue 11, pp. 1568-1573 (1966) https://doi.org/10.1364/JOSA.56.001568

[5] W.C.Walker et al. - Photoelectric Yields in the Vacuum Ultraviolet
J. Appl. Phys. 26, 1366–1371 (1955) - https://doi.org/10.1063/1.1721909

CO2 deexcitation

[6] Y.Itikawa - Cross Sections for Electron Collisions With Carbon Dioxide
J. Phys. Chem. Ref. Data 31, 749–767 (2002) https://doi.org/10.1063/1.1481879

Radiation Trapping

[7] T.Holstein - Imprisonment of Resonance Radiation in Gases
Phys. Rev. 72, 1212 – Published 15 December, 1947 https://doi.org/10.1103/PhysRev.72.1212

Ion Induced Secondary Emissions

[8] K.T.A.L. Burm - Calculation of the Townsend Discharge Coefficients and the Paschen Curve Coefficients
Contrib. Plasma Phys. 47 (3) (2007) 177–182, https://doi.org/10.1002/ctpp.200710025

[9] M. Klas, Š. Matejčík, B. Radjenović, M. Radmilović-Radjenović, - Experimental and theoretical studies of the direct-current breakdown voltage in argon at micrometer separations
Phys. Scr. 83 (4)(2011) 045503 - http://dx.doi.org/10.1088/0031-8949/83/04/045503

[10] R.Buschhaus et al. - Ion-induced secondary electron emission of oxidized nickel and copper studied in beam experiments
Plasma Sources Science and Technology February 2022 31(2) - 10.1088/1361-6595/ac4c4c

Penning Transfer Processes

[11] O.Sahin - Transfer reactions leading to Penning effect - RD51 Meeting 5 – 9 October 2020

Thanks !!

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