SWEATERS Project
Monte Carlo Simulations of Micromegas at low pressure

Status Report for RD51 Mini Week

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Giuseppe Antonelli

on behalf of the SWEATERS TEAM @ INFN Pisa

INFN PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

SWEATERS Project

SWEATERS (Space Weather Ena Radiation Sensors) project

MPGD operating at low-pressure as an innovative instrument for low energy atom detection, spectrometry, and imaging. Mainly focused on the detection of Energetic Neutral Atoms (ENA) in space

Synergetic project:

- Funded by INFN National Scientific Commission 5 (Jan 2020 – Dec 2022)
- INAF/INFN SWEATERS project funded by ASI (July 2022 – July 2023)

Basic requirements (nice to have)

Energy range	**1-100 keV**
Energy resolution	**20%**
Field-of-view (FOV)	60° polar x 60° azimuth - 2D
Angular resolution	**5° x 5°**
Particle flux	10^2 – 10^5 ENAs/(cm^2 s sr)
Mass channels	**H**, He, **O** discrimination

Challenging technology R&D

- Micromegas (MM) operating at low pressures (30-100mbar - far below their ideal operating conditions) to increase the ENA track length
- Carbon foil entrance window for ENA – Ion conversion

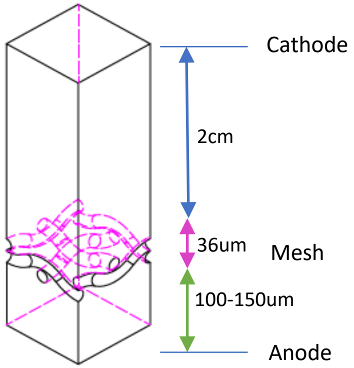
Main investigation areas

- MM performance characterization (gains vs Ar/CO2 Mix, pressure, drift/avalanche voltage, gap size)
- Charge amplifiers on Mesh signals and related DAQ/analysis software
- Readout electronics on Strips signals and related DAQ/analysis software
- MC simulations at low pressures
- Optimization of the MM mechanical support frame, of the gas system, of the detector slow control

Quick overview on SWEATERS test bench

Micromegas

- Two 20 mm drift height MM in use: a BULK MM with nominal 128um avalanche gap (MM128) in the initial phase of the project; a BULK MM with 192um gap (MM192)
- Actual avalanche gaps estimated to be **100um** and **150um** respectively by fitting first Townsend coefficient $\alpha/p = Ae^{-\frac{Bpd}{V}}$ with measures at NTP
- Mesh is a 18um thick Nickel interlaced grid (woven mesh)
- Standard gas mixture is Argon 93% / CO2 7%
- At low pressures (100mbar) typical electric fields are 25 V/cm in drift zone and 18-40KV/cm in avalanche zone (100-150um). Mesh is grounded.



Sources

- **5.9KeV X-ray Fe55**: measurements with this source are the basis for the experimental and simulation set-up
- 1-5KeV He ions beam

Test bench Set-up

- Custom charge amplifier connected to the mesh; charge amplifier output multiplexed to the Oscilloscope, MCA and frequency counter
- Picoammeter connected to the mesh for high accuracy mesh current measurements
- At low pressure we got stable operating conditions constantly controlling the gas mixture-flux-pressure and MM temperature. Stability of these parameter is critical
- Readout electronics on strips (SRS with APV25), triggered using a comparator on the mesh signal

Measurements (X-ray source)

Measurements of number of electrons per X-ray calculated as $N_{(e-/x\text{-}ray)}$ = mesh current/event rate. We estimate an experimental error of about 10% - 20%. So far, the following measurements have been carried out:

MM128 and MM192 @NTP - MM128 and MM192 @100mbar, 293K - MM192 @50mbar, 293K

Sweaters MC simulations set-up

GOAL

- Identify and quantify physical processes relevant to the overall gain, energy and tracking resolution
- Quantify their relationships with gas mixture, pressure, temperature and avalanche gap
- Make predictions for gaps up to 500um

MC Drift Region

- Geant4 framework using fast simulators
  - Degrad for x-rays (5.9 keV x-rays)
  - SRIM for atoms
  - Garfield++/Magboltz for electron drift
- Electric field maps:

  Uniform field: 300V/cm @NTP, 25 V/cm @50-100mbar
- Source

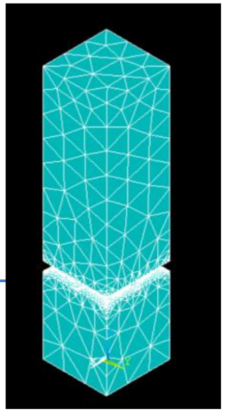
  X-ray @ 5.9KeV

MC Avalanche Region

- Based on Garfield++ (AvalancheMicroscopic), Magboltz
- Electric field maps

  ANSYS/ComponentAnsys123 with step ≈ 0.3 - 0.5um
- Source

  primary electrons from Drift region at 400um from mesh

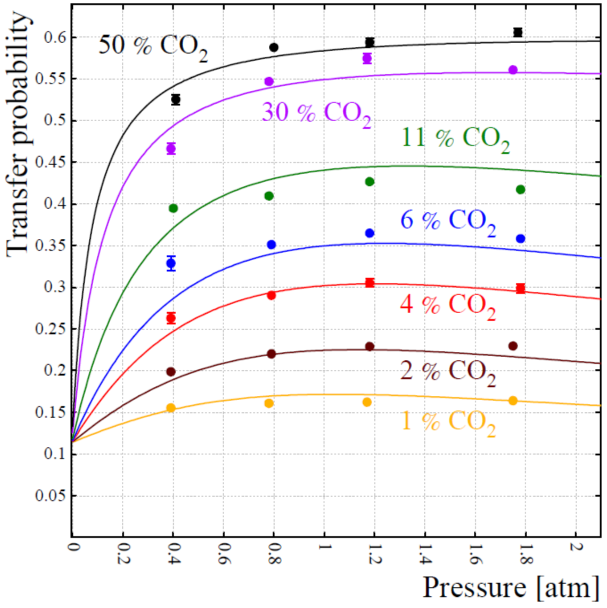


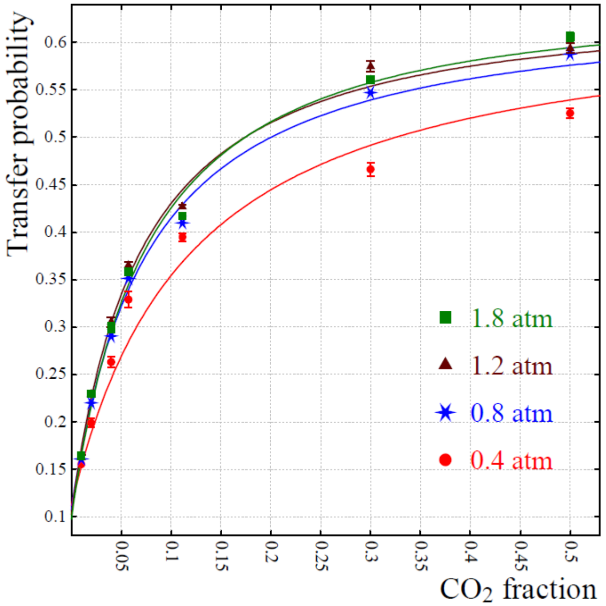
Penning transfer rate estimate for MC Simulations

r_{Pen} = penning transfer rate, the fraction of excitation-induced ionizations implies corrections to the 1st Townsend Coefficient, $\alpha_{Pen} = \alpha(1 + r_{Pen}\frac{f^{exc}}{f^{ion}})$

$$r_{Pen}(p,c) = \frac{a_5 p^2 (1-c)^2 + a_1 pc + a_4 c + a_3}{a_6 p^2 (1-c)^2 + pc + a_2}$$

Ar2*- CO2 Excimers
Ar*- CO2 Collisional Ionization
Ar*- Y Radiative energy transfer





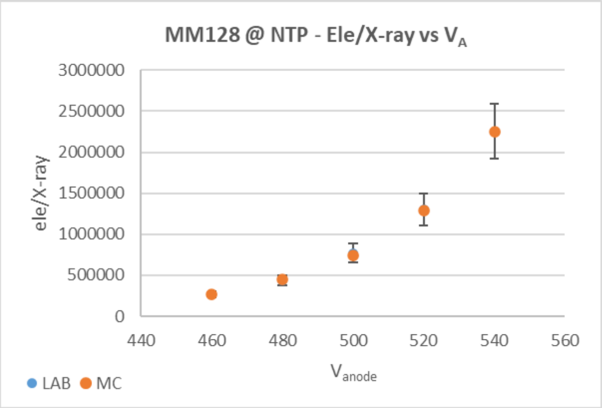
Parameter	Value
a_1	0.627898 ± 0.018083
a_2	0.041394 ± 0.008297
a_3	0.004716 ± 0.001512
a_4	0.001562 ± 0.017566
a_5	0.002422 ± 0.001171
a_6	0.027115 ± 0.005836

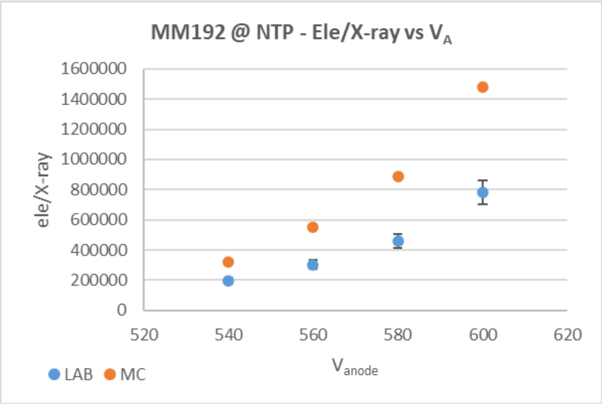
Transfer rates for Ar 93% CO2 7% should be:

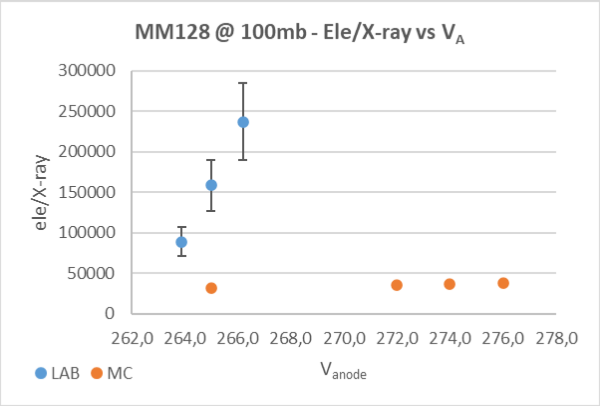
@NTP	$r_{Pen} \approx$ 0.38-0.42
@100 mb	$r_{Pen} \approx$ 0.19-0.25
@50mbar	$r_{Pen} \approx$ 0.16-0.20

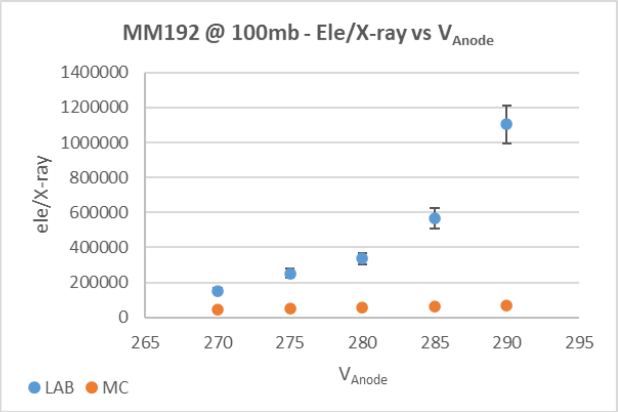
Ref: O.Sahin,…,R.Veenhof - High-precision gas gain and energy transfer measurements in Ar–CO2 mixtures – 2015
O.Sahin - Transfer reactions leading to Penning effect - RD51 Meeting 5 – 9 October 2020

Initial findings from MC simulations









*Throughout the presentation: **Gain** = Number of final electrons per X-ray , **LAB** = experimental measurements at laboratory*

Overall gain (final electrons/X-ray)

MM128	MC ≈ Lab @NTP	MC ≈ 1/5 Lab @100mbar
MM192	MC ≈ 1.9 Lab @NTP	MC ≈ 1/3…1/15 Lab @100mbar

Mesh Transparency (% of primary electrons passing through the mesh)

MM128	93-98% (Eval/Edrift ~100) @NTP	55% (Eval/Edrift ~ 700) @100mbar
MM192	87-89% (Eval/Edrift ~90) @NTP	55% (Eval/Edrift ~ 500) @100mbar

Drift Region MC findings

X-ray conversion rate and primary electrons per X-ray (about 200) correspond to what was expected at 5.9Kev, so **drift simulation seems OK**

Avalanche Region MC findings

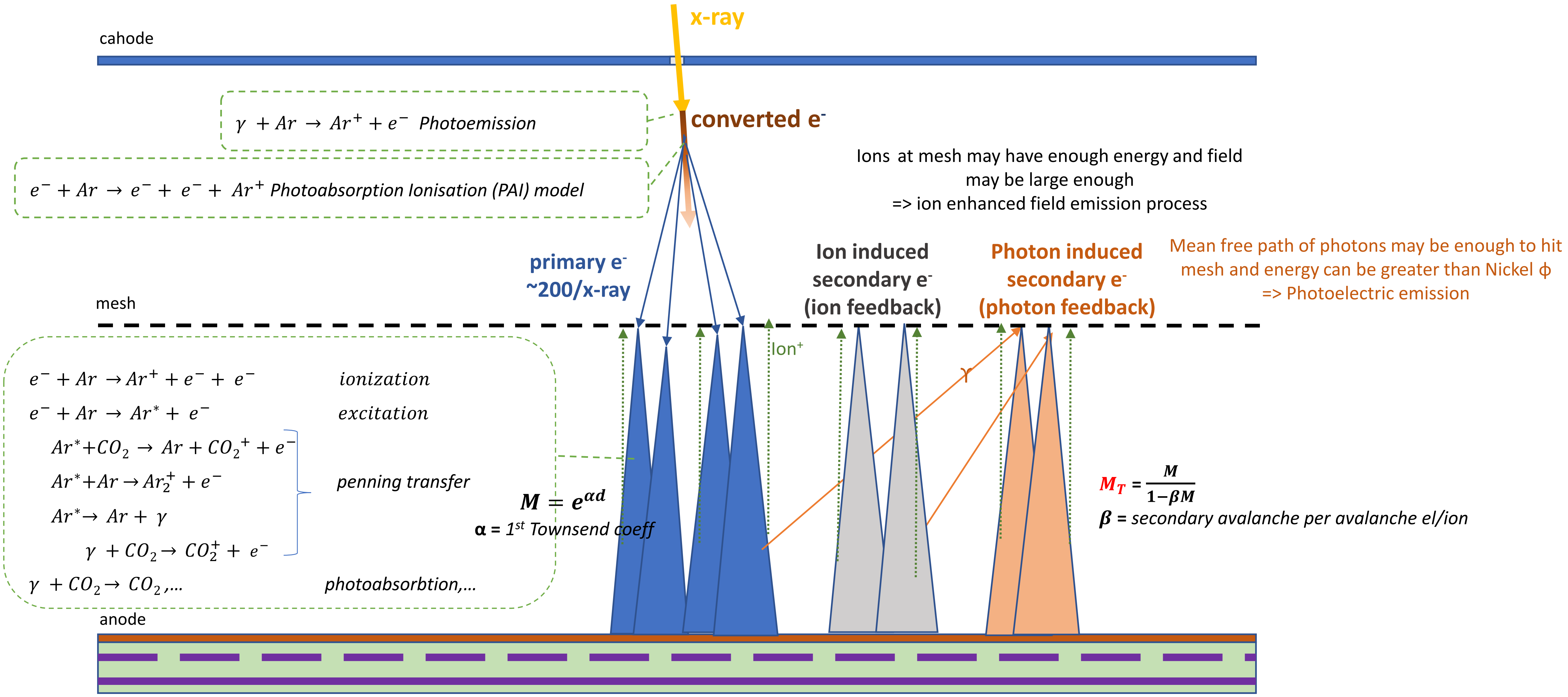
@100mbar both MM show a **low multiplication factor** in the avalanche region and a corresponding low growth compared to lab and **low transparency**

α calculated in the last part of the avalanche gap (where E is uniform) and calculated by Magboltz are close and both significantly lower than lab:

α_{MC} = 497 cm-1 (last 50um) , $\alpha_{Magboltz}$ = 530 cm-1 (via generate gas table), α_{Lab} = 600-630 cm-1 (estimated with MM128 V_{Anode} = 265V)

➔ ADDITIONAL PHYSICAL PROCESSES MUST BE CONSIDERED

New physical processes added to Garfield++



Garfield++ changes to cope with MM @ 50-100mbar

A. Collision steps handling

- Enable Null Collision Steps to update electron energy on null collisions
- Increase Null Collision frequency at lower pressures (e- mean free path is ~ 0.3/2.7/4.8 um @NTP/100/50mbar)

=> Increased transparency and gain

B. Detailed deexcitation mode

Detailed deexcitation and photon absorption/trapping modelling in Garfield++ is a «proof of concept» developed (a few years ago) to cover **Argon** as excited gas (44 states) and **CO2**, CH4, C2H6, C2H2, CF4, C4H10 as quenching gases. It is complex but a great value in Garfield++ and very useful in our context as it affects photoelectric secondary emissions

- Use detailed deexcitation mode instead of Penning transfer rate mode

C. Photoelectric induced secondary electrons

- Use PhotonTransport in Garfield++
- New code to handle photons hitting the mesh (as Ansys medium) so generating secondary electrons

D. Ion induced secondary electrons

- New code to add transport of ions inside AvalancheMicroscopic (based on TransportMC with some corrections for low pressures)
- New code to handle ions hitting the mesh (as Ansys medium) so generating secondary electrons

E. Breakdown handling

- Flag electrons according to the origin of the avalanche to which they belong to (primary, photon induced, ion induced)
- Dynamic calculation of βM to control avalanche growth to prevent program hanging (discharges)

Secondary emissions in MC Simulations

Photon induced secondary emission (photoelectric effect)

- E_Υ > 5 eV (Nickel work function), $E_e = E_\Upsilon - 5$
- Yield on Nickel surface from R.Cairnis – Journal of the optical society of America 56/11, 1578-1573(Nov 1966)
- E_Υ : 11-15eV (1100-800 Å) => yield: 0.02 – 0.13
  - No angular distribution is applied and mesh surface status (clean, oxidized,…) impacts Photoelectric Yield
- Quencher % is relevant: more CO2 less feedback.
- Laboratory measurements with different gas mixtures indicate that Photon Feedback should be the prevalent process of secondary emission

(@50mbar abs gain CO2 8% ~ ½ abs gain CO2 7%)

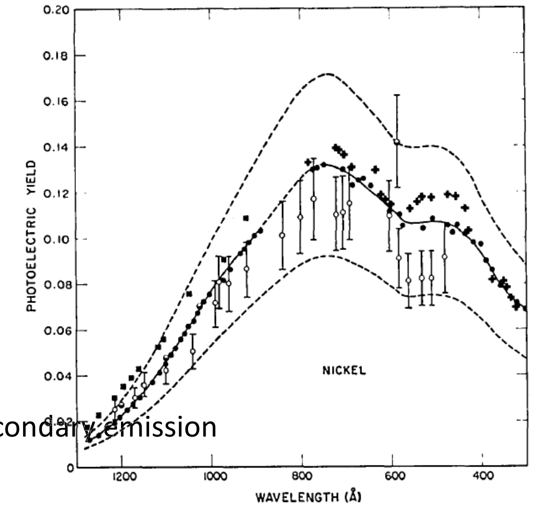


FIG. 3. Photoelectric yield of nickel: ● present data, + present data (second sample), ◐ data of Hinteregger and Watanabe,[9] ■ data of Watanabe *et al.*,[11] – – – – curves representing the present data ±30%, ○ data of Walker *et al.*[10]

Ion induced secondary emission

- Literature on this topic is difficult to apply to our context: the process which seems applicable is the ion enhanced field emission but also the Ion impact secondary emission should be examined.
- Yield on Nickel surface is from L.Burm - Contrib. Plasma Phys. 47/3, 177-182 (2007)

$\Upsilon = \frac{kT}{E_F} e^{-\frac{W}{kT}}$ where W (work function) = 5 eV, E_F (Fermi energy) = 13.97 eV, KT = ion energy (around 1 eV @ 50-100mbar)

At KT = 1eV we have Yield ≈ 0.0005

(In M.Klas et al. - Experimental and theoretical studies of the direct-current breakdown voltage in argon at micrometer separations - Physica Scripta (2010) yield around 0.005-0.01 have been measured for steel and aluminium under our own conditions of Ion energy = 1eV and E/p = 200-1000 V cm-1 Torr-1)

Garfield++ «tuning»

Tuning strategy

At this stage of work our **strategy** is

- identify key points where to force adjustments that allow the measurements to be reproduced
- then investigate further the code and related physical processes which affect the identified key points

A. Penning transfer rate

Penning Transfer rates from deexcitation appear to be too high:

- Reduction of Watanabe-Katsuura penning transfer contribution
- Reduction of Hornbeck-Molnar ionisation

B. Radiation absorption/trapping

Collision frequency of discrete absorption lines seems to reduce photon mean free path too much:

- Reduction of collision frequency of radiation absorption lines

C. Photon vs Ions induced secondary emission

Some tuning of yields is applied taking into account that MM128/MM192 might have different surface conditions and therefore justify different yields

@100mbar photon feedback seems to be the only process needed to explain our measures and gain trend versus mix.

@50mbar simulations give low gains without Ions induced contributions, which in turns, does not meet the gain of our instrument as function of the gas mixture. For these working conditions, @50mbar, our experimental set-up suffers of important uncertainties on gas mixture and stable pressure (long transition times).

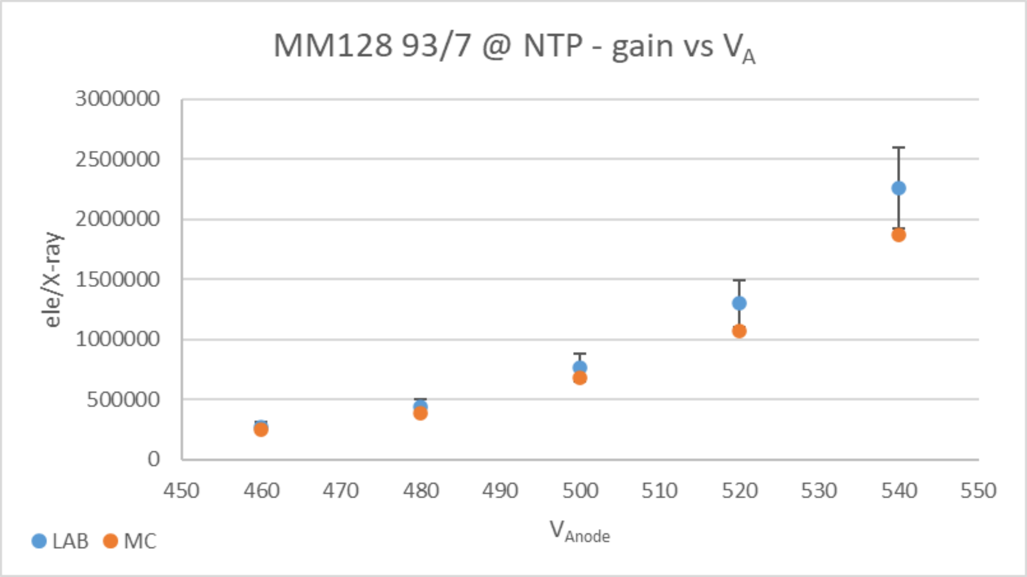
MC gain @NTP

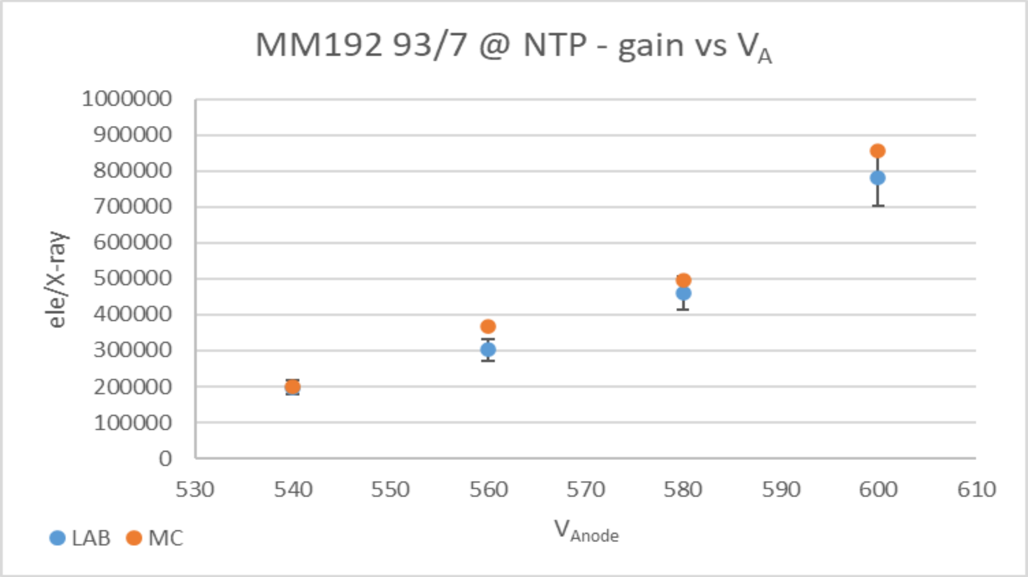
MM128 @ NTP

- No secondary electrons emission
- Penning adjustment (resulting r_{pen} = 0.43)
- ➢ Good agreement measures – MC simulations
- ➢ Transparency ≈ 98%, FWHM ≈ 10-15%

MM192 @ NTP

- No secondary electrons emission
- Penning adjustment (resulting rpen = 0.36-0.38)
- ➢ Good agreement measures – MC simulations
- ➢ Transparency ≈ 98% , FWHM ≈ 15-20%





MC simulations at the current stage of tuning have some adjustments applied and a limited number of events

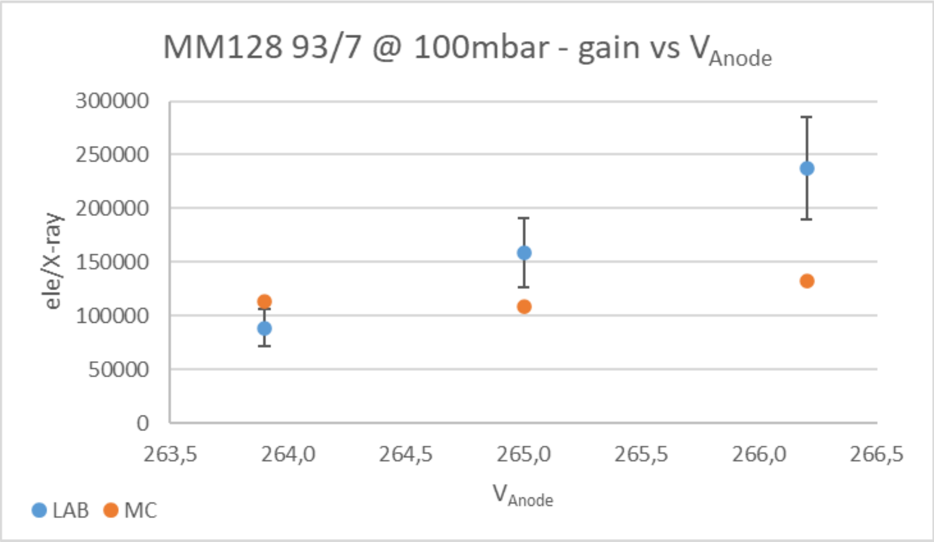
MC gain @100mbar

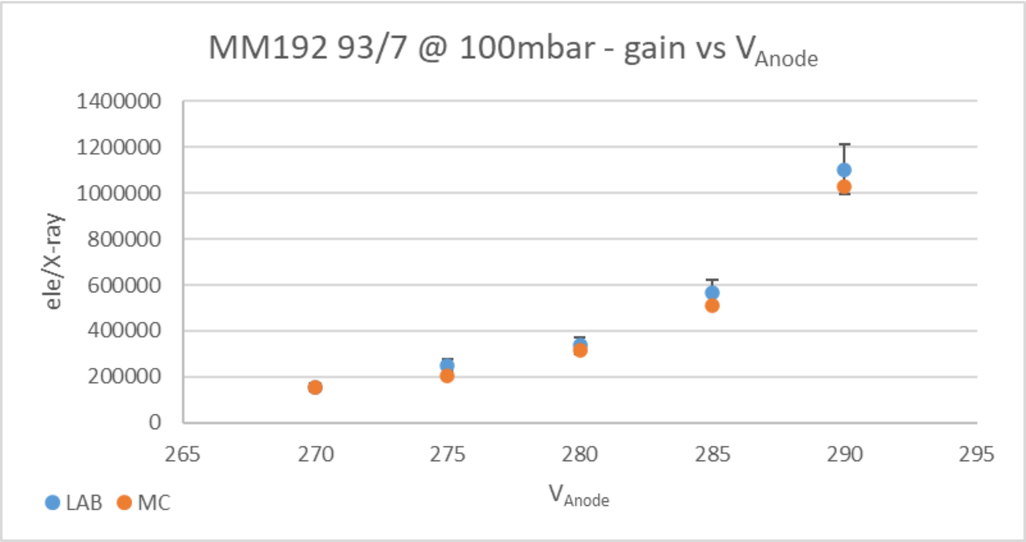
MM128 @ 100mbar

- Photoelectric and ion induced secondary emission
- Penning adjustment (resulting $r_{pen} \approx 0.25$)
- Reduced collision frequency of discrete absorption lines
- Increased photoelectric emission Yield (50%, mesh differs)
- ➢ Reasonable agreement measures-MC (ΔV_{Anode} very small ≈ 0.5%)
- ➢ Transparency ≈ 95%, FWHM ≈ 30-40%
- ➢ $\beta \approx 0.0026$

MM192 @ 100mbar

- Photoelectric and ion induced secondary emission
- Penning adjustment (resulting $r_{pen} \approx 0.26$)
- Reduced collision frequency of discrete absorption lines
- ➢ Good agreement measures – MC simulations
- ➢ Transparency ≈ 85-90%, FWHM ≈ 30-50%
- ➢ $\beta \approx 0.0013$



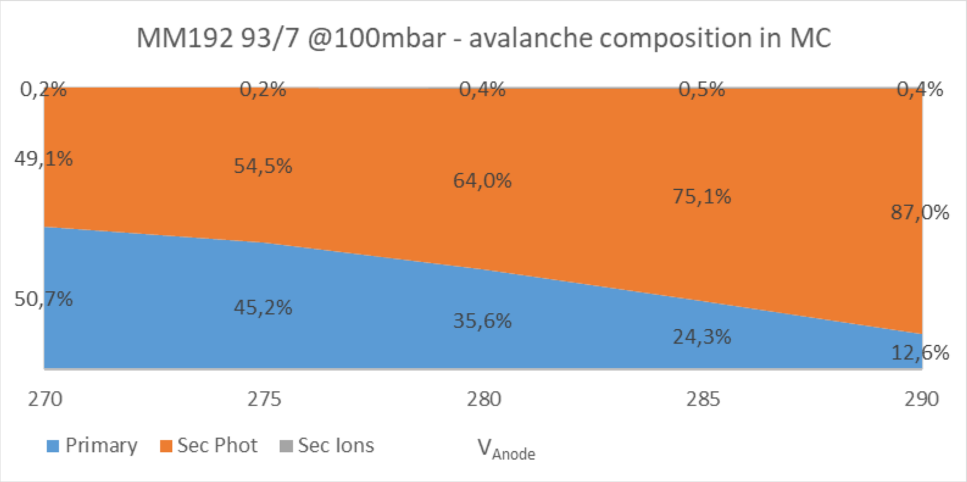


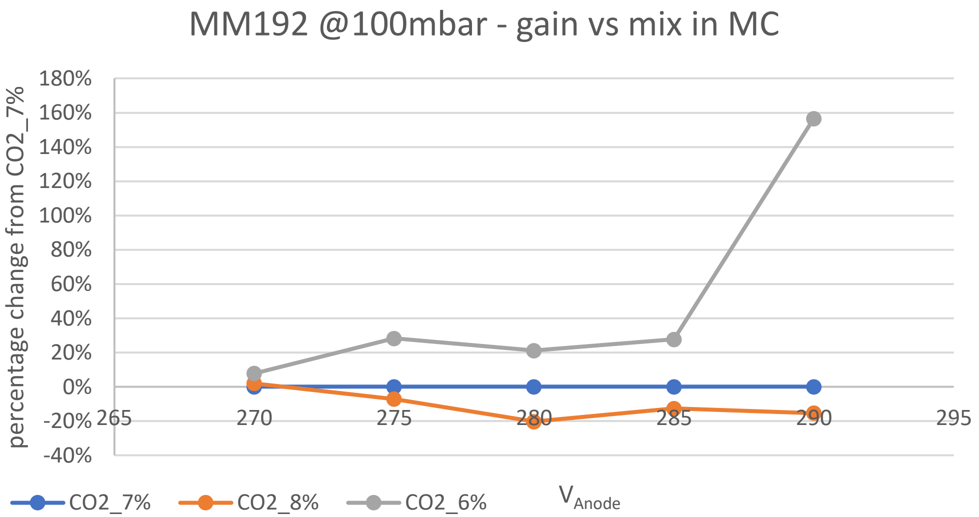
MC simulations at the current stage of tuning have some adjustments applied and a limited number of events

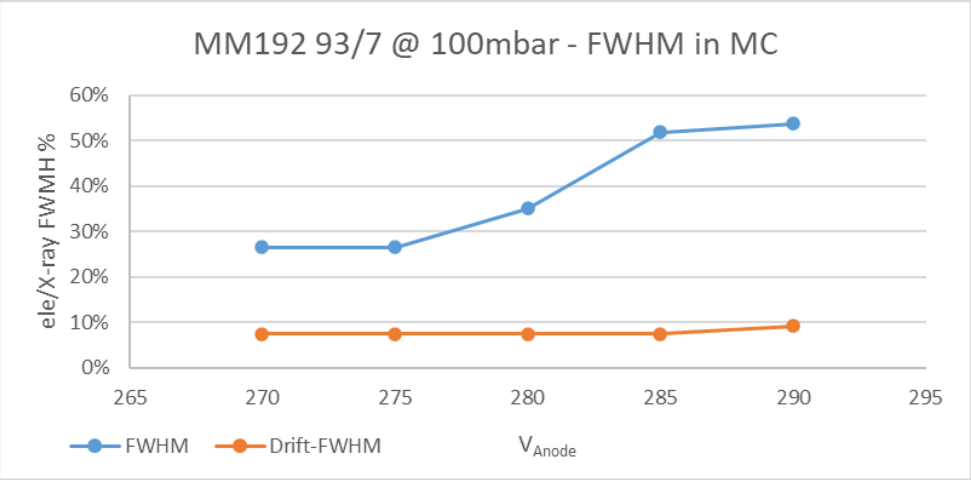
Inside MC gain of MM192 @100mbar

MM192 @ 100mbar

- Contribution of photoelectric secondary emission grows with V_{Anode}
- Ions induced secondary emission on mesh doesn't seem relevant
- Gain decreases with the increment of CO_2 % as observed in LAB
- FWHM significatively grows up to 50% as observed in LAB







MC simulations at the current stage of tuning have some adjustments applied and a limited number of events

Open points and next actions

A. MC simulations @ 50mbar

MC simulations at 50mbar are still far from the experimental laboratory measurements

- Find a coherent parametrization under various conditions able to match also measures at 50mbar

B. Secondary emissions

Parametrization of photoelectric and ion induced secondary emissions is still very preliminary

Refine the implementation of photoelectric and ion induced physical processes (ion enhanced field and ion impact secondary emissions)

C. Deexcitation and radiation absorption/trapping processes

A relevant reduction (1/100 – 1/1000) of collision frequency due to discrete absorption lines has been applied

- Review code which affects photon generation and absorption/trapping. Excitation cross sections at higher K should also be checked

D. Penning transfer rate

Penning transfer rate resulting from detailed deexcitation code has been reduced by 1/3 to be in line with expected values

- Review code which affects penning transfer rate

E. Null-collision alghoritms

At 50mbar also transparency seems to be too low (60%) and it must be investigated

- Apply Runge-Kutta integration for the free-flight steps (as suggested by Schindler)

F. New MM configurations

- Based on current setting for MM128/192, make predictions @100mbar with gaps between 200-500 um and hopefully find an optimal gap/voltage combination to have good gain with the minimum or, better, null contribution from feedback processes.

Suggestions or corrections around this MC simulation activity are welcome. It is also appreciated the mention of any other process to be considered in our model and to be implemented in the code.

Thanks !!