Performance and stability of a High Granularity Resistive Micromegas at high particle rates.

M. DELLA PIETRA[1,2]

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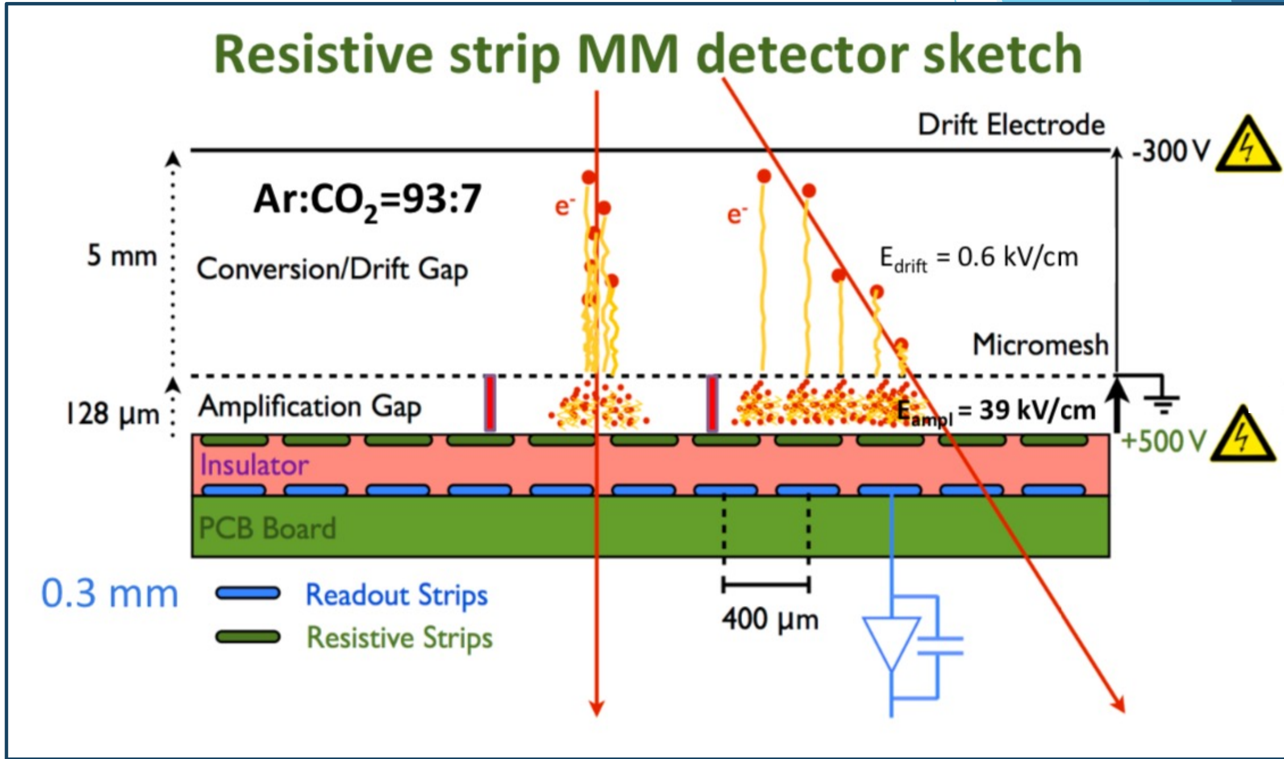
Contents

Our ancestor: Resistive Micromegas for ATLAS New Small Wheel upgrade

- A metallic micro mesh separates the drift volume (2-5 mm thick) from the amplification volume (~100 µm thick);
- electrons and ions produced in the amplification volume are collected in ~1 ns and ~100 ns respectively;
- spatial resolution < 100 µm independently from the incoming track angle;
- resistive anode strips on the top of the readout strips (with insulator in between) to suppress discharges.
- The "ATLAS" resistive strip micromegas with a wide surface (about 2 m^2) will operate at a moderate rate of about 20 KHz/cm2.



Small-Pad MM: detector concept and motivation

- Micromegas technology aiming at precision tracking in high-rate environment without efficiency loss up to several MHz/cm^2

Possible applications:
- ATLAS very forward extension of muon tracking (Large eta Muon Tagger – option for future upgrade),
- Muon Detectors and TPC at Future Accelerators,
- Readout for sampling calorimeters,
- …

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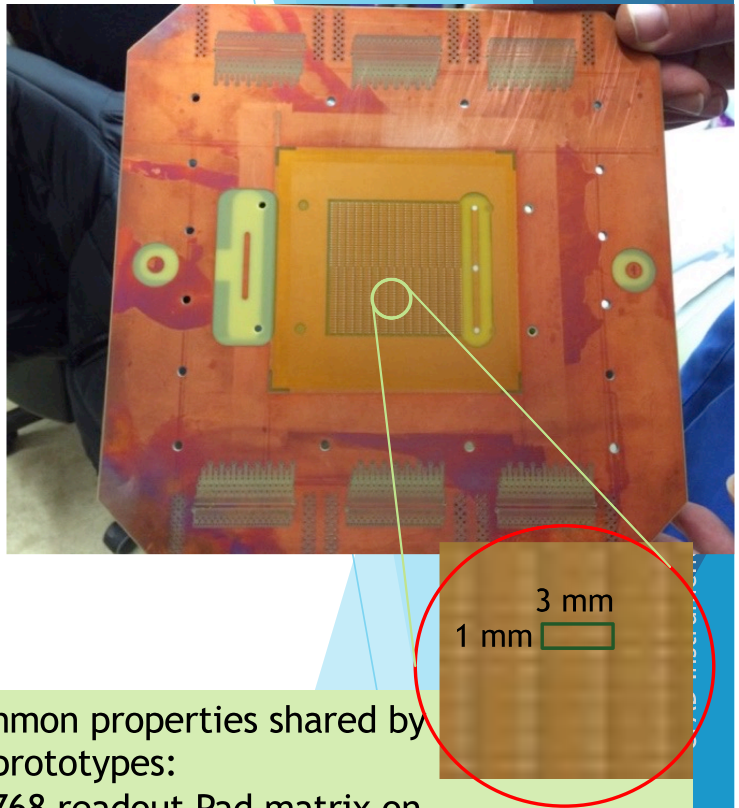
- Readout plane segmented in pads $O(mm^2)$ to ensure high rate capability and good spatial resolution in both coordinate.



Common properties shared by all prototypes:

- 768 readout Pad matrix on 4.8 x 4.8 cm^2 active area;
- Circular pillars with r = 200 μm, height 100-120 μm (bulk technique) and 6 mm pitch;

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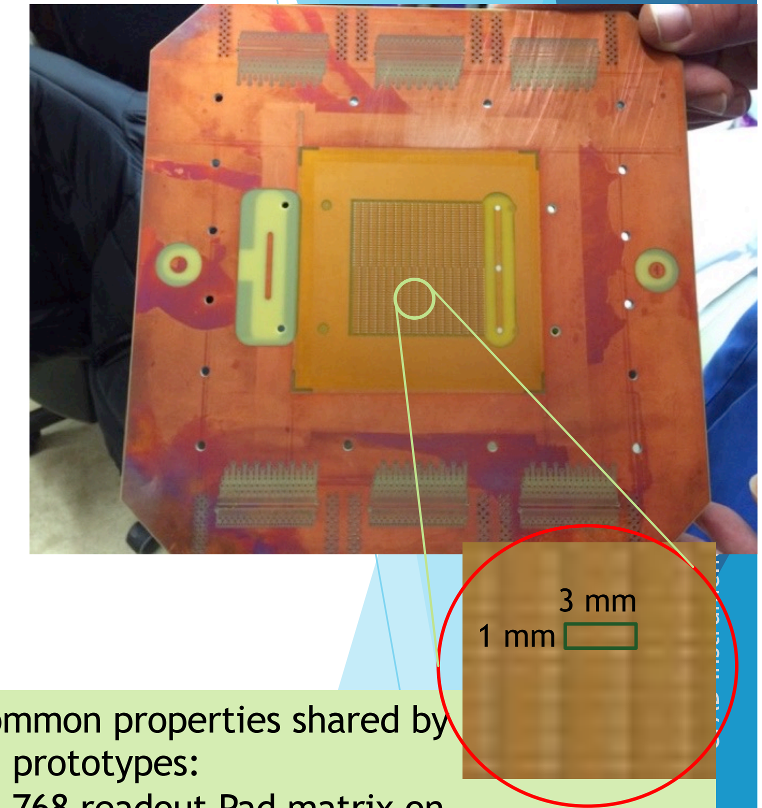
- **The 1x3 mm^2 PAD geometry and the requirement on the high-rate capability rule a new spark protection resistive layout:**
- **The optimization of the resistive layout has been the focus of this R&D project during its first stage**
  - **Several prototypes built and tested with different resistive protection schema**

- Technical solution inspired by a similar R&D by COMPASS and other groups within RD51 Collaboration;
- R&D started in 2015 (INFN and University of Napoli and Roma3) in collaboration with CERN and with the CERN PCB Workshop (Rui De Olivera) for prototype construction.



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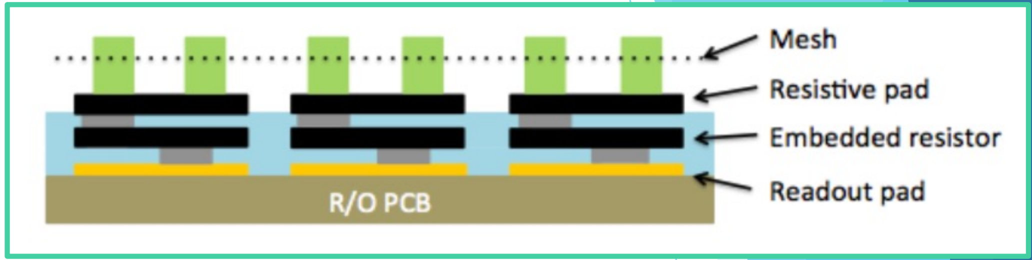
- For large detector area it's mandatory to properly scale the signal routing to the detector border:

- **The second stage R&D is ongoing and is focused on developing a detector with FE elx back-bonded to the detector in order to solve the problem of signal routing when scaling to larger surface**

Spark suppression resistive layout

- Scheme 1: PAD-Patterned embedded resistor



- Two planes of independent screen printed carbon resistive pads with the same geometry of copper readout pads;
- The overlapped pads in the different planes are interconnected by silver vias, as shown in the picture.
- Each pad has an overall impedance ranging within (3 – 7 MΩ)

Spark suppression resistive layout

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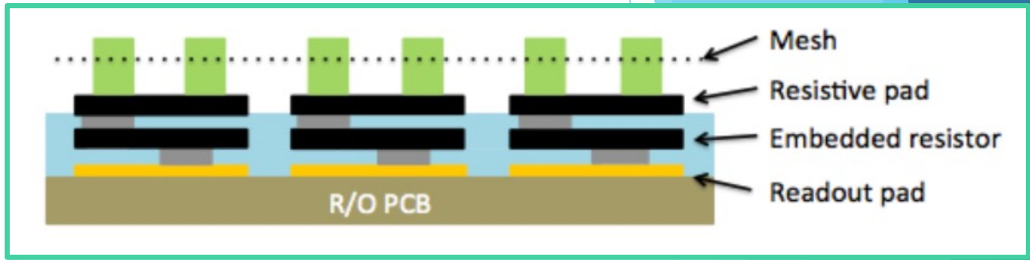
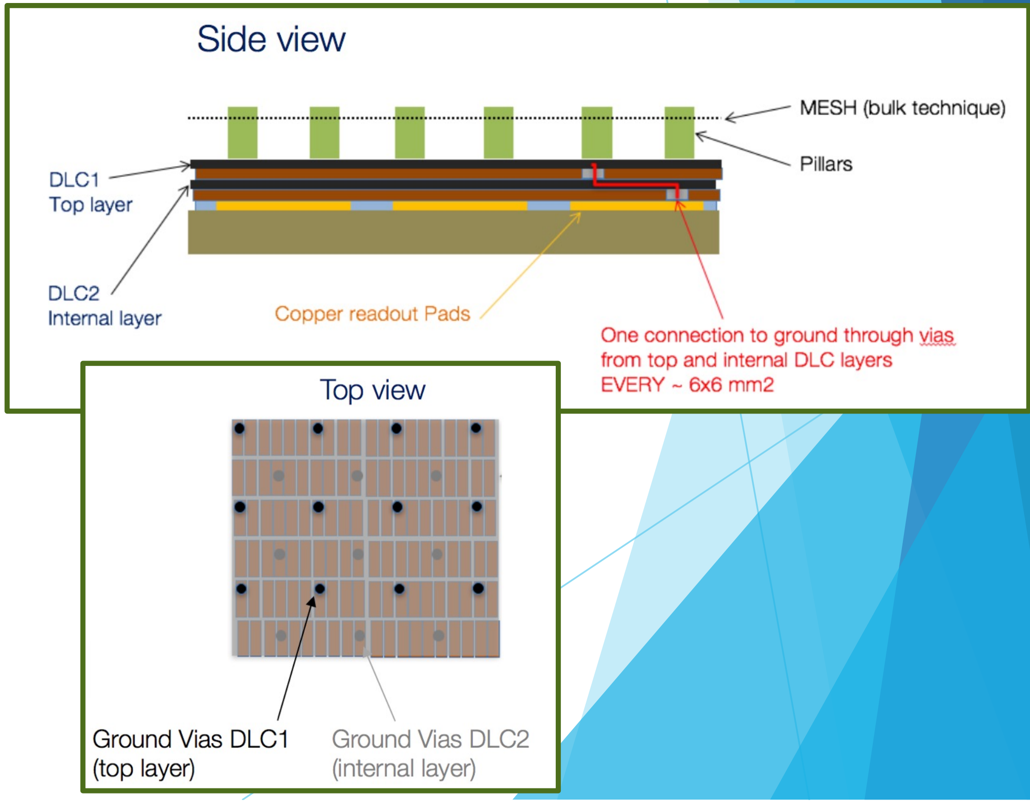


- Scheme 2: Double DLC (Diamond Like Carbon) uniform resistive layer

- Two continuous resistive DLC layers (5 - 50 MΩ/□) interconnected between them and to the readout pads with network of conducting links with the pitch of few mm, to evacuate the charge;
- Same concept of uRWell (see G.Bencivenni et al. 2015_JINST_10_P02008)
- It simplifies the production sequence;
- 2nd generation of prototypes with improved detector assembling technique referred as SBU (Sequential Build Up) see Rui De Oliveira talk @ INSTR2020
- Several prototypes: DLC-50, DLC-20, SBU1, SBU2



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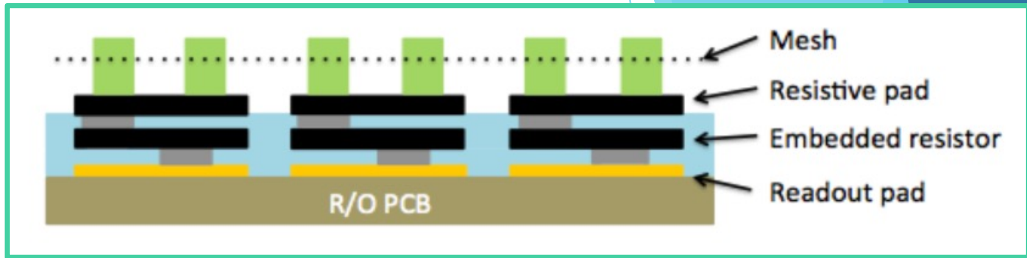

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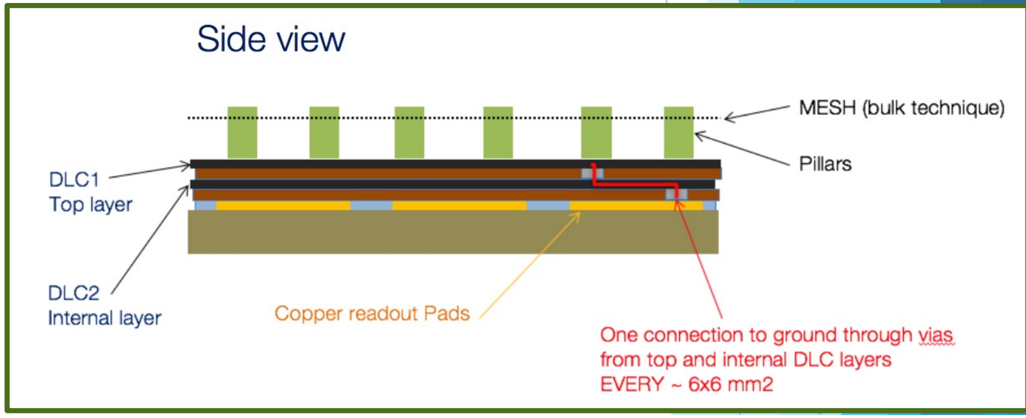
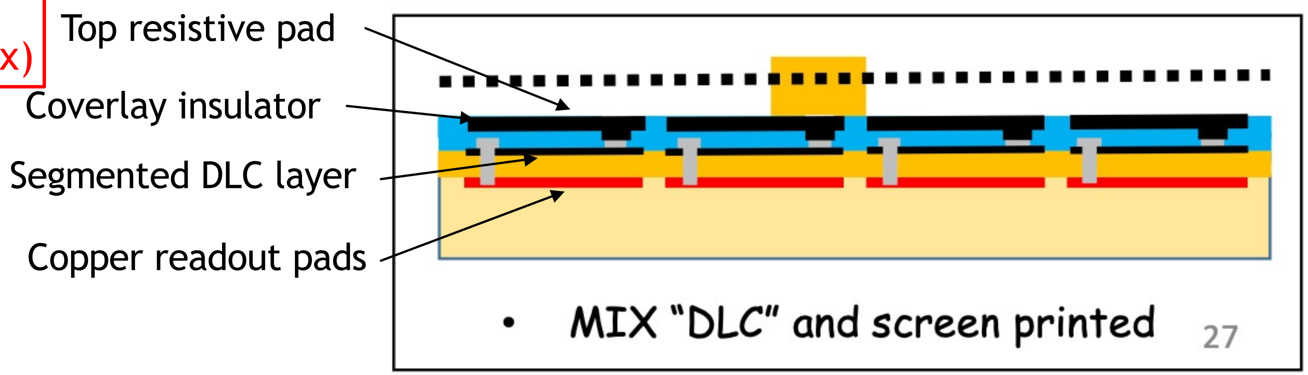


- Scheme 3: Mixed solution (PAD-P-Mix)
  - The resistive pad facing the amplification gap is always screen printed
  - The intermediate resistor is done by DLC layer
  - Much more similar to scheme 1



Characterization of the detectors: Gain

Measurements have been carried out by means of two radiation sources:
- ^{55}Fe sources with two different activities
  - Low activity (measured rate ~ 1 kHz)
  - High activity (measured rate ~ 100 kHz)
- 8 keV Xrays peak from a Cu target with different intensities varying the gun excitation current

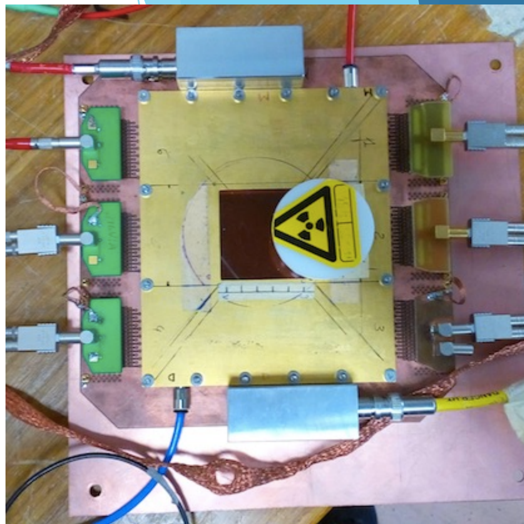
Different gain measurement methods:
- Reading the detector current from the mesh (or from the readout pads) and counting signal rates from the mesh
- Signals amplitude (mesh) from a Multi Channel Analyser.

At higher rates
- Rates measured at low currents of the X-Ray gun
- Extrapolating Rate Vs X-Ray-current when rates not measurable or not reliably anymore

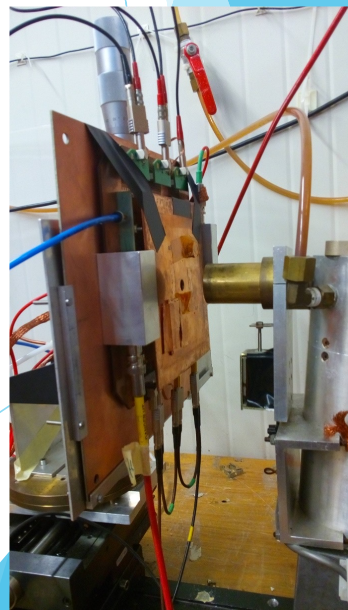
Comparison between prototypes has been done @ fixed gain (~ 7 x10^3)

Gas Mixture Ar: CO_2 93:7
Choosen as the safest gas to operate under high irradiation for long time

^{55}Fe source



Xrays Gun

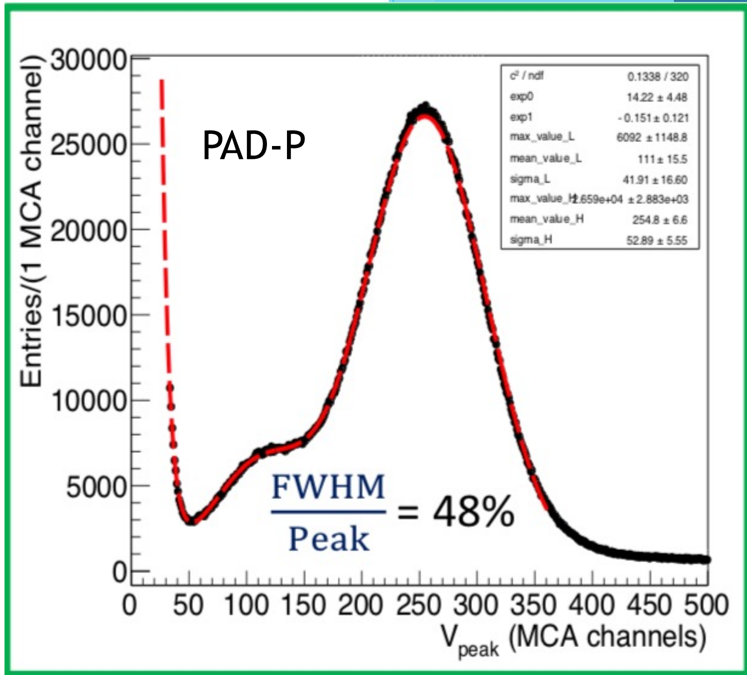


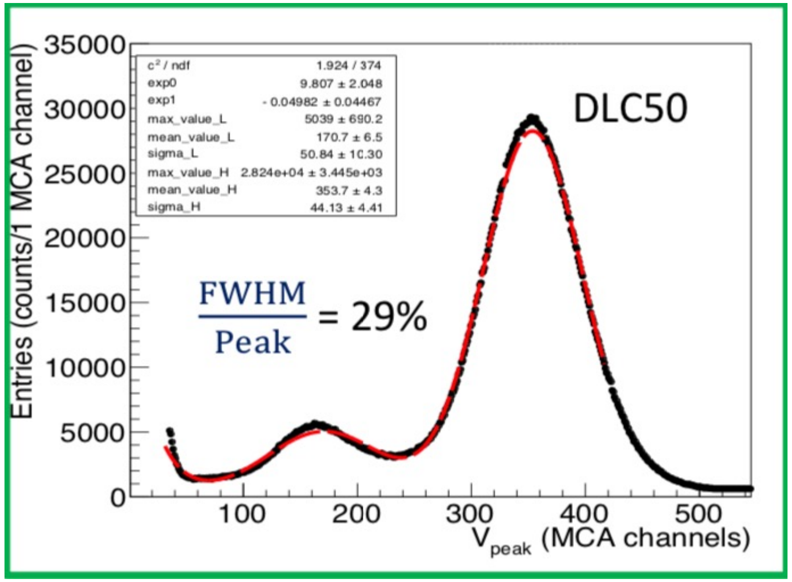
PAD-P vs DLC: Energy resolution

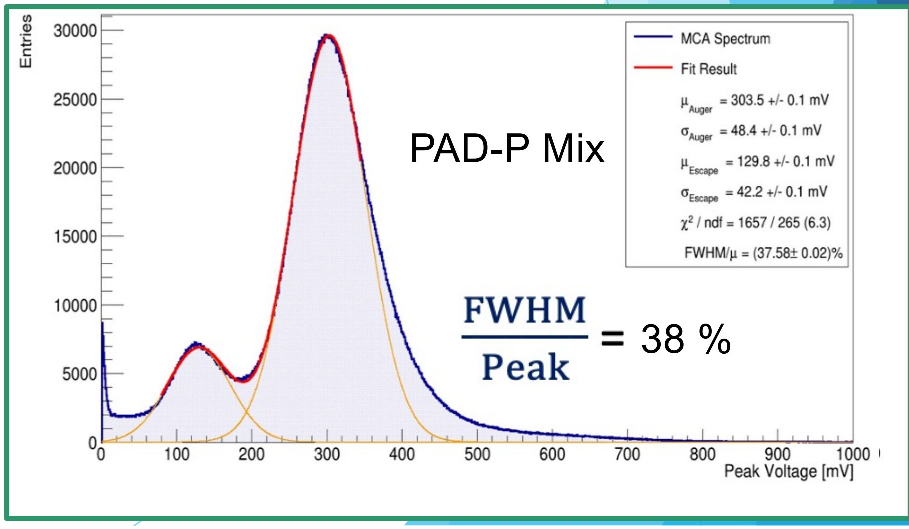
Energy resolution measured looking at the ^{55}Fe spectrum

The DLC resistive protection scheme shows a better energy resolution with respect to the "PAD-P" and "PAD-P-Mix" schema due to:

- more uniform electric field
- no pad border effects





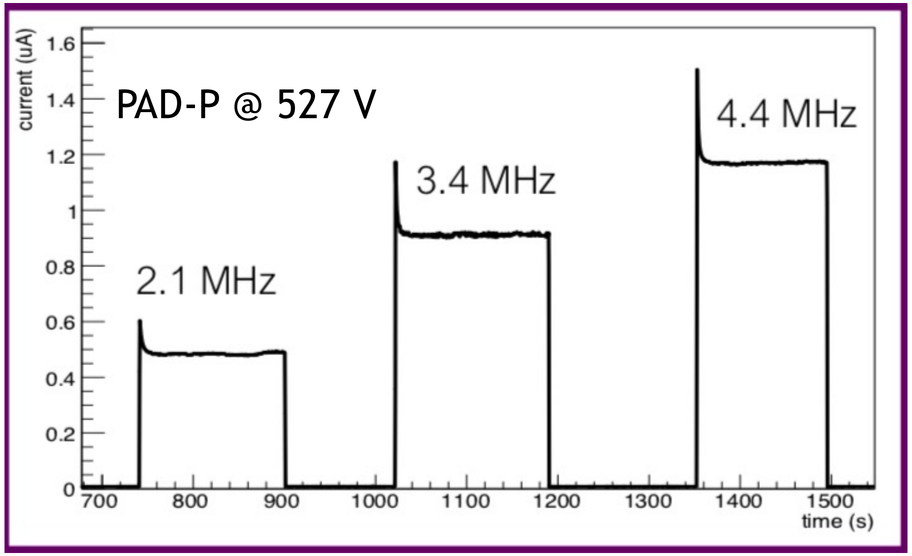


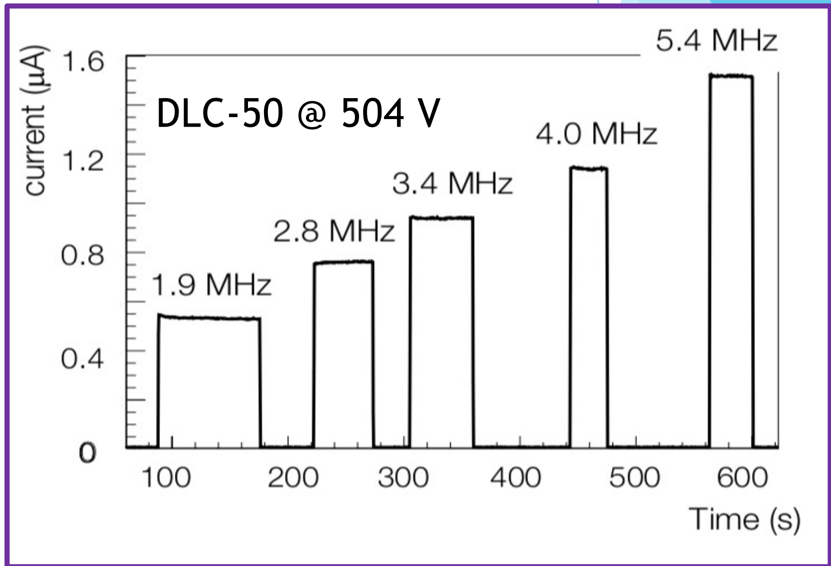
PAD-P vs DLC: Detector current vs time: charging up

Current measurement Vs Time during cycles of X-Rays irradiation

All prototypes with Pad-Patterned resistive layout (both scheme 1 and 3) shows sizeable effects of charging-up (gain reduction by ~20%) in **current as function of time.**

- PAD-P reduction of gain with time: a possible explanation is due to dielectric charging-up of exposed Kapton surroundings the resistive pads. **Still under investigation.**
- DLC detectors do NOT show any sizeable charging-up effects (expected from the uniformity of the resistive layer and from the absence of exposed dielectric, with the exception of the pillars).

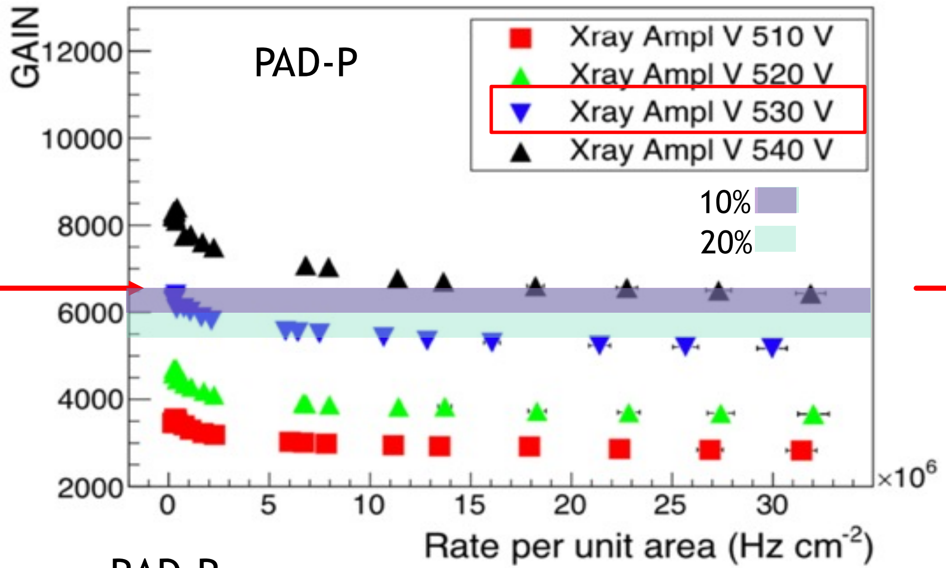


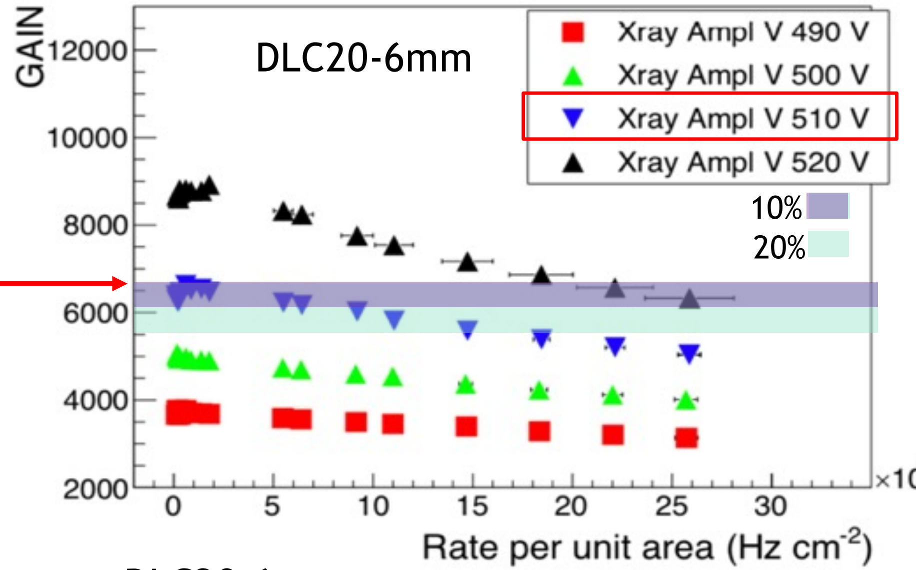


Gain vs Rate up to 30 MHz/cm^2

- X-rays exposure area 0.79 cm^2 (shielding with 1cm diameter hole)

Gain DLC20 > PAD-P.
Same gain if HV PAD-P = HV_DLC + (20-30) V





PAD-P

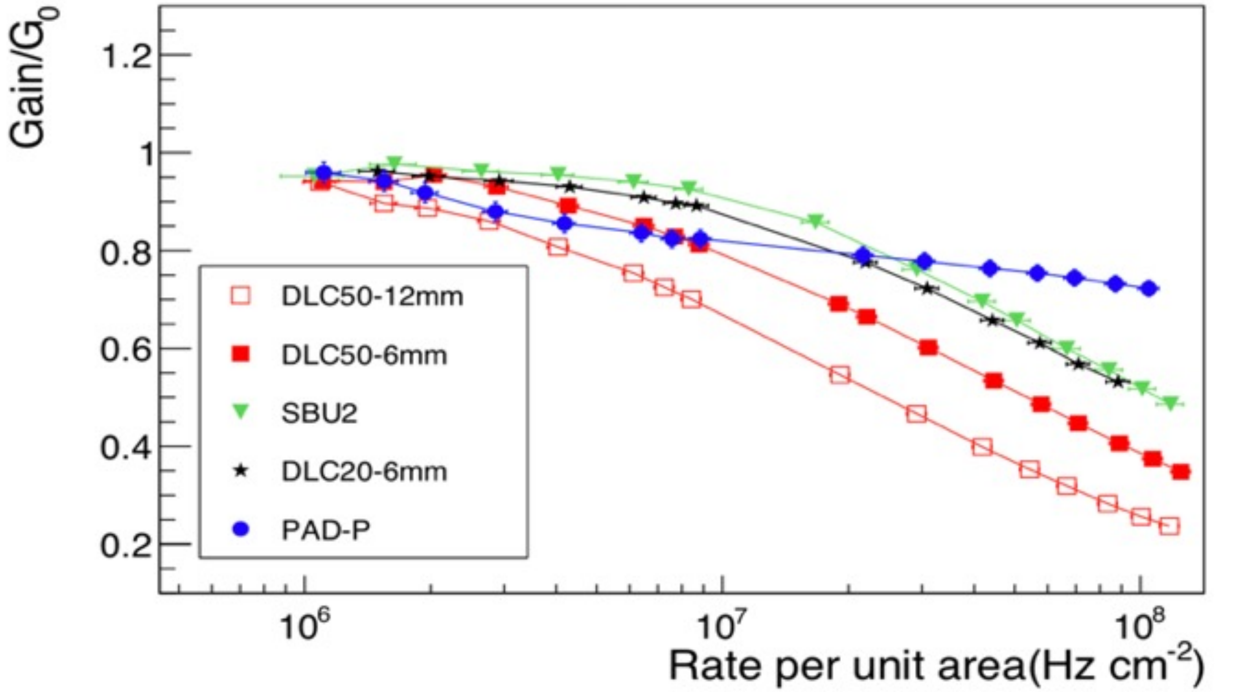
- Significant gain drop at "low" rates dominated by charging-up effects
- Negligible ohmic voltage drop for the individual pads for rates > few MHz/cm2
- Relative drop:
  - -10% at ~ 3 MHz/cm^2 at 530 V
  - -20% at ~20 MHz/cm^2 at 530 V

DLC20-6mm

- Almost constant gain at "low" rates (up to few MHz/cm^2.
- Significant ohmic voltage drop at higher rates
- Relative drop:
  - -10% at ~10 MHz/cm^2 at 510 V
  - -20% at ~20 MHz/cm^2 at 510 V

Rate capability for resistive different layout schemes

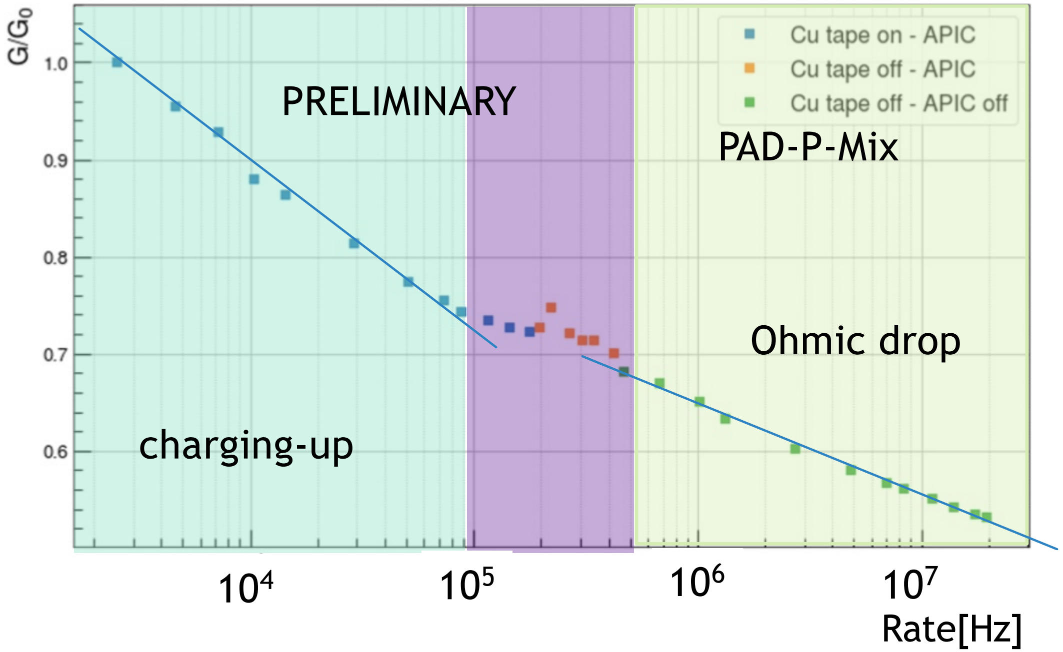
- PAD-P shows a sizeable gain drop due to the charging-up at lower rates (up to few MHz/cm^2) but a lower ohmic drop due to the fact that each pads behaves as an independent resistor to ground.
- DLC20, SBU have a comparable behaviour in the explored region (up to ~100 MHz/cm^2):
  - mean values of the resistance between first and second DLC protection foils are almost the same
  - For rates greater than 20-30 MHz/cm^2 they shown a higher gain drop w.r.t. PAD-P
- As expected DLC20 and SBU better than DLC50 (due to lower resistivity)

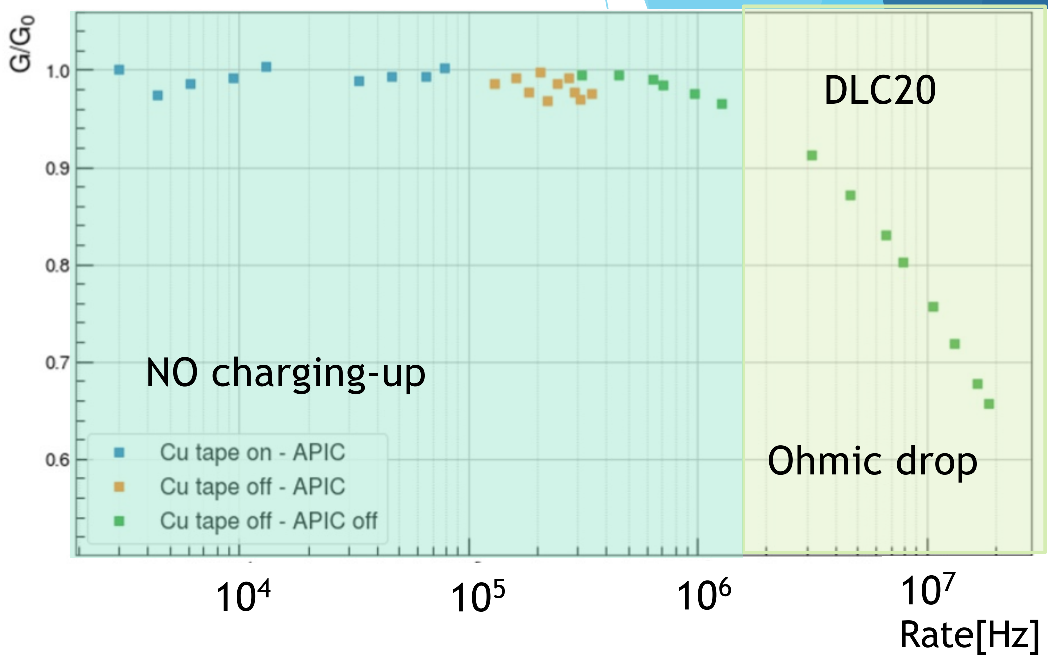


Clear difference between the regions with 6mm and 12 mm grounding vias pitch (the larger the vias pitch the greater the impedance to ground seen by the collected charge)

Gain vs Rate over 4 orders of magnitude

- X-rays exposure area 0.79 cm^2 (shielding with 1cm diameter hole)

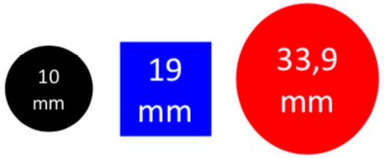


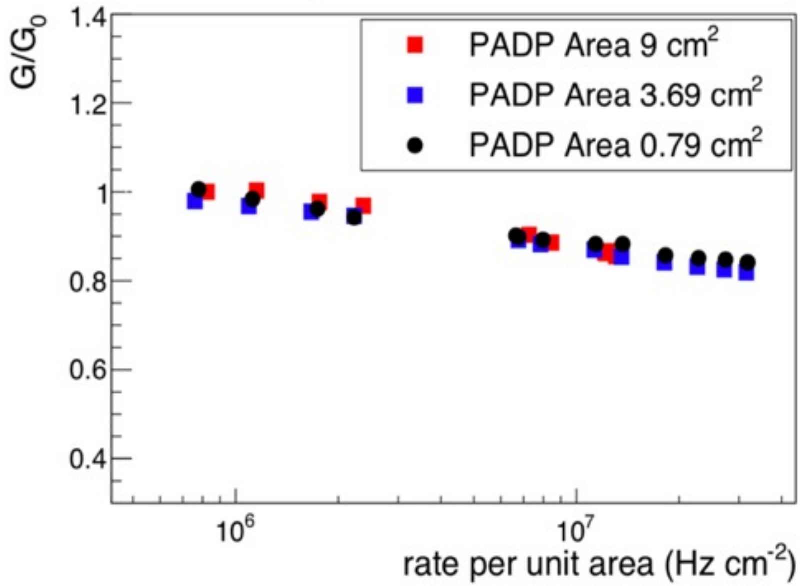


- Significant gain drop at "low" rates dominated by charging-up effects as for PAD-P schema
- Negligible ohmic voltage drop for the individual pads for rates between 0,1 and ~2 MHz/cm2

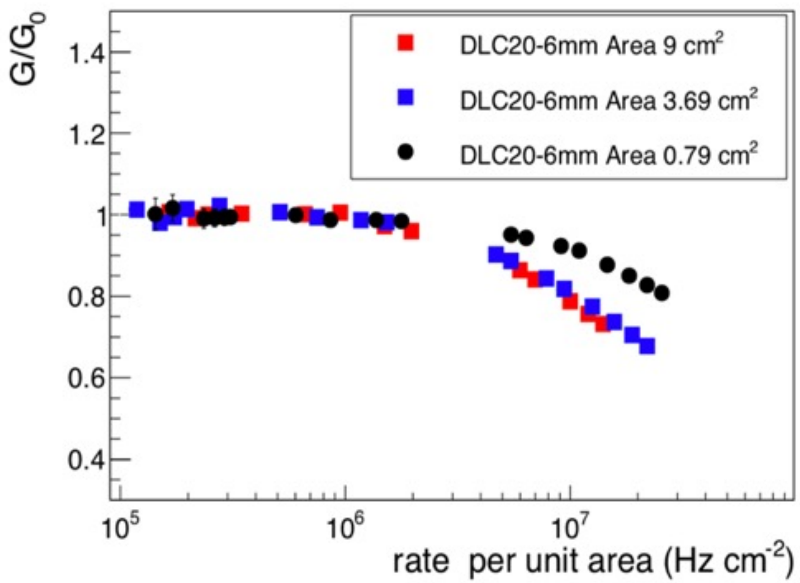
- Almost constant gain at "low" rates (up to few MHz/cm^2.
- Significant ohmic voltage drop at higher rates

Rate capability dependence on irradiated area





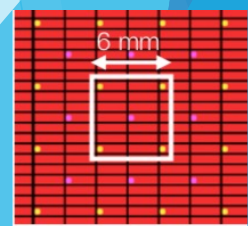
PAD-P



DLC20-6mm

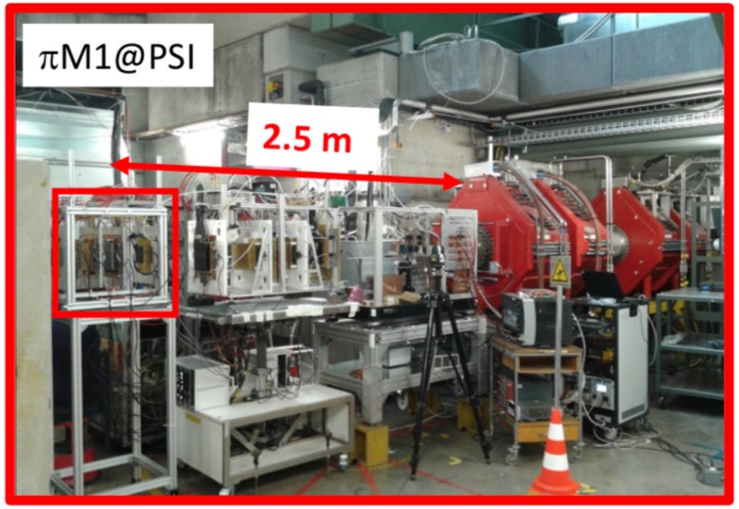
- Thanks to independent pads there is no dependence on the exposed area.

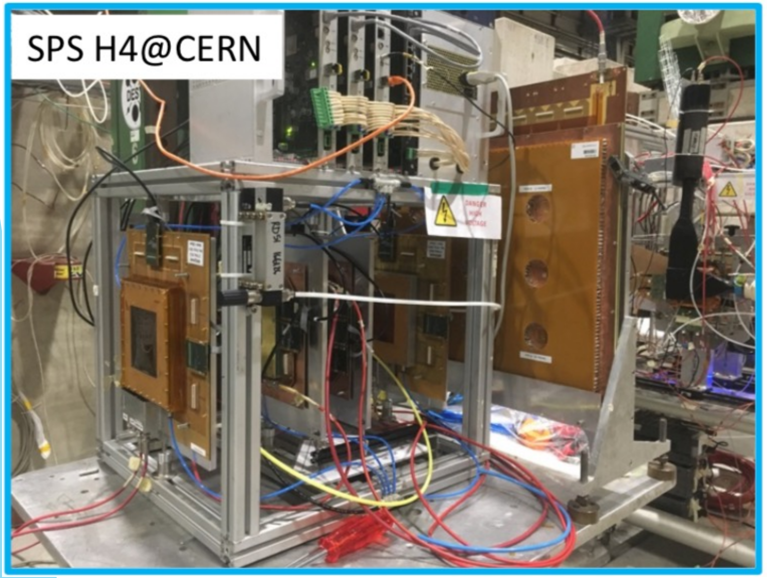
- For rates greater than 5 MHz/cm2 a dependence of the gain drop from exposed area is measured.
- For irradiated surface bigger than ~3.7 cm^2 (~10 times the grounding vias (0.6 x 0.6) cm^2 cell) gain drop does not scales with the area.



Test beam (CERN and PSI) results and performances

2016/17	2018	2019
SPS H4@ CERN μ,π @ 150 GeV/c low/high rates	SPS H4@ CERN μ,π @ 150 GeV/c π @ 80 GeV/c	πM1@PSI π @ 300MeV/c p contamination ~7%
PAD-P, DLC50	DLC50 – DLC20	PAD-P, DLC20, SBU1 SBU2

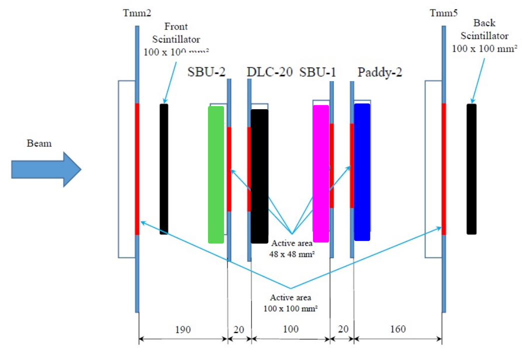




Typical setup:

- Two small scintillators for triggering
- Two double coordinate (xy) bulk strips micromegas (10 x 10 cm2) for tracking
- Small-pads MM in between
- gas mixture: Ar/CO_2=93/7 pre-mixed
- DAQ: SRS+APV25

SBU2 DLC20 SBU1 PADP



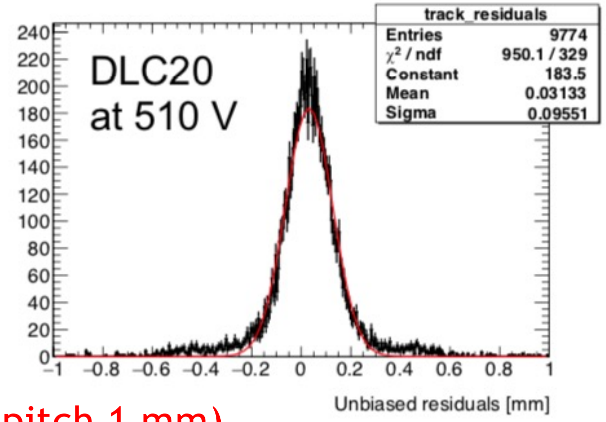
Spatial resolution and cluster size (TB @ CERN)

Position resolution:

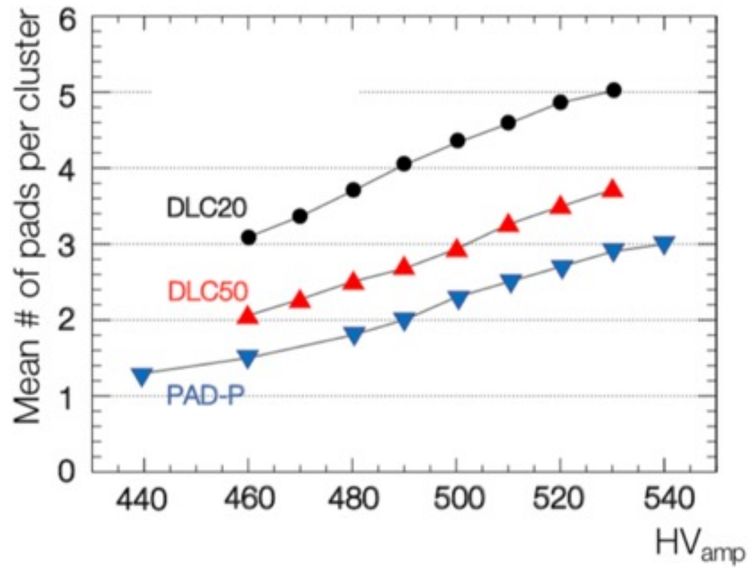
Cluster residual w.r.t. extrapolated position from external tracking chambers

$$\sigma_{resol} = \sqrt{\sigma^2_{resid} - \sigma^2_{track}}$$

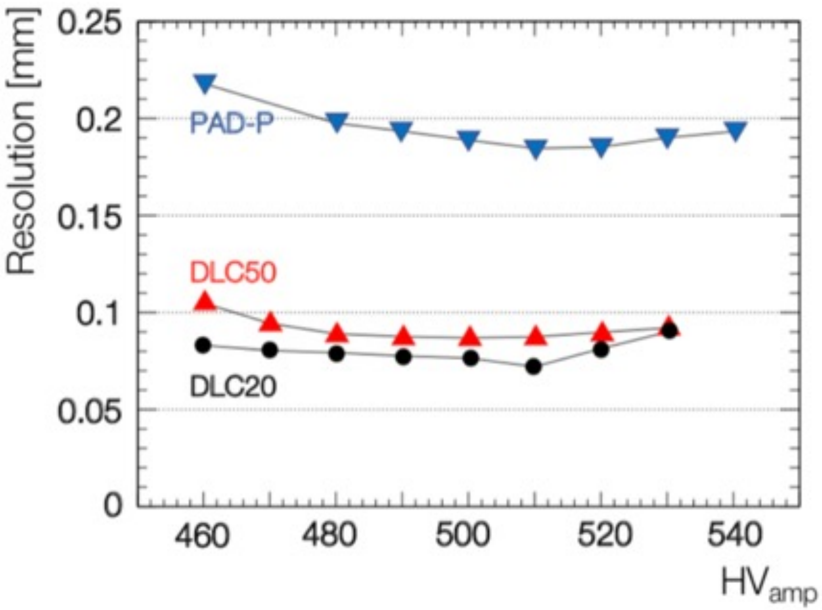
$(\sigma_{track} \simeq 50\ \mu m)$



Cluster size vs. HV



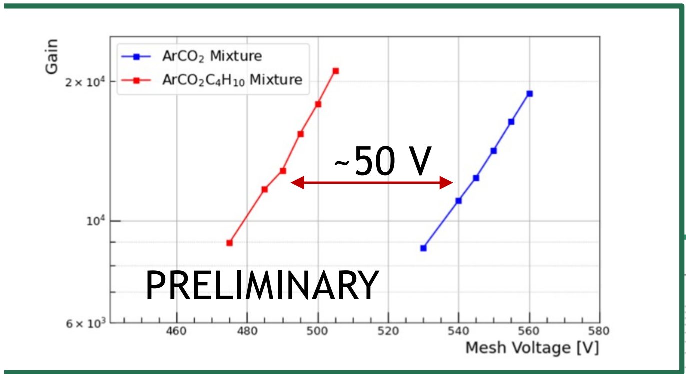
Precision coordinate (pad pitch 1 mm)

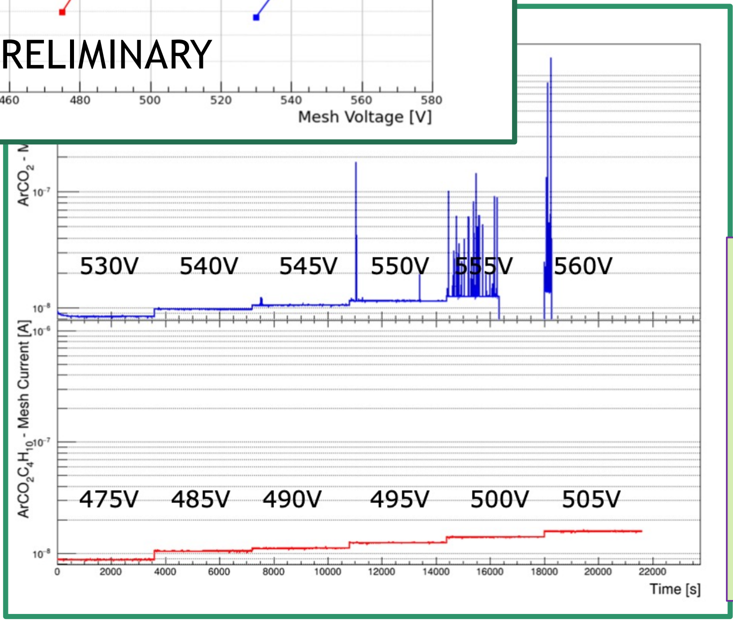


- More uniform charge distribution among pads in the clusters leads to:
  - Significant improvement of spatial resolution of the DLC prototypes (pad charge weighted centroid)
  - The lower is the resistivity of the DLC layer the higher is the size of the cluster

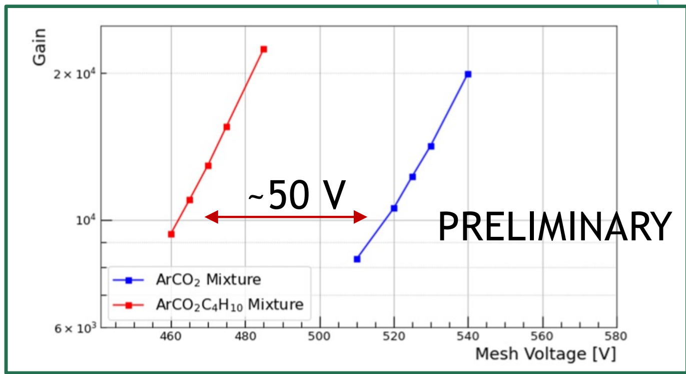
Studies with different gas mixture:

- Added 2% of Isobutane to our standard gas mixture in order to improve the detector stability
  - From Ar:CO_2 93:7 to Ar:CO_2:iC_4H_{10} 93:5:2
- Very high gain reachable in very stable conditions (^{55}Fe sources)

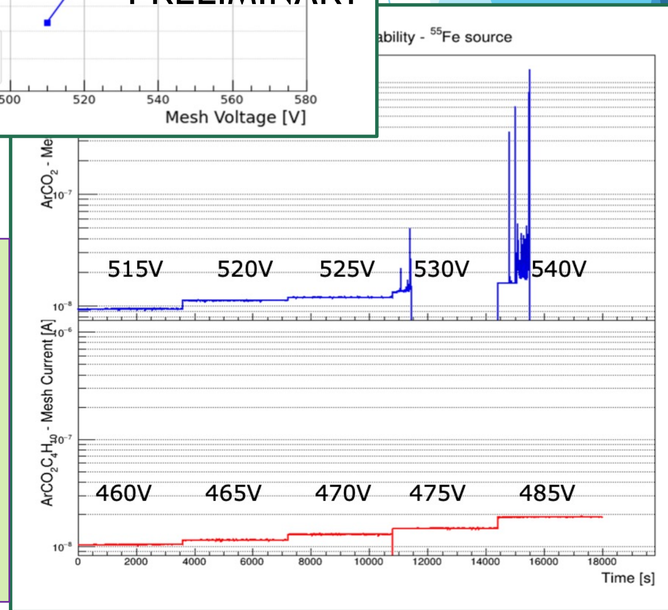




PAD-P-Mix



DLC20

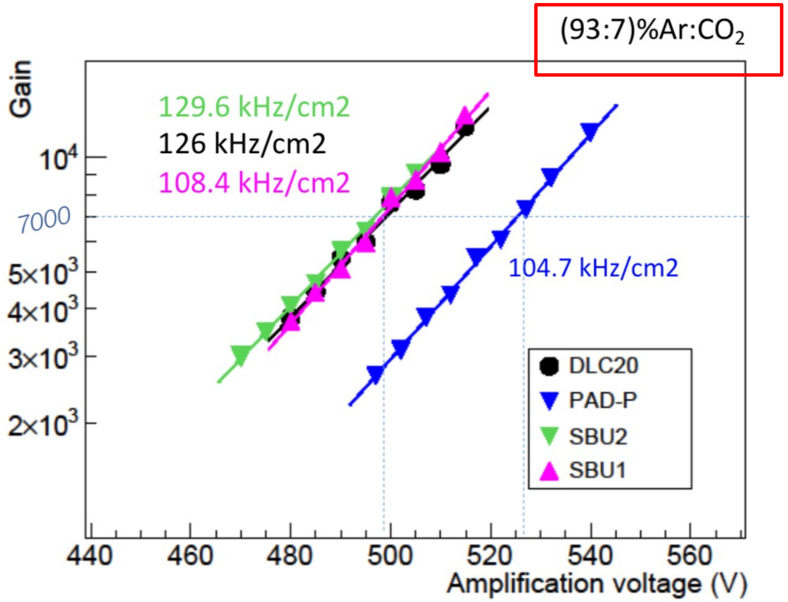


Without isobutane
Instability for Gain > ~15k

With isobutane
Stable operation up to
Gain >20k
(not tested further)

Studies on sparks probability (TB @PSI)

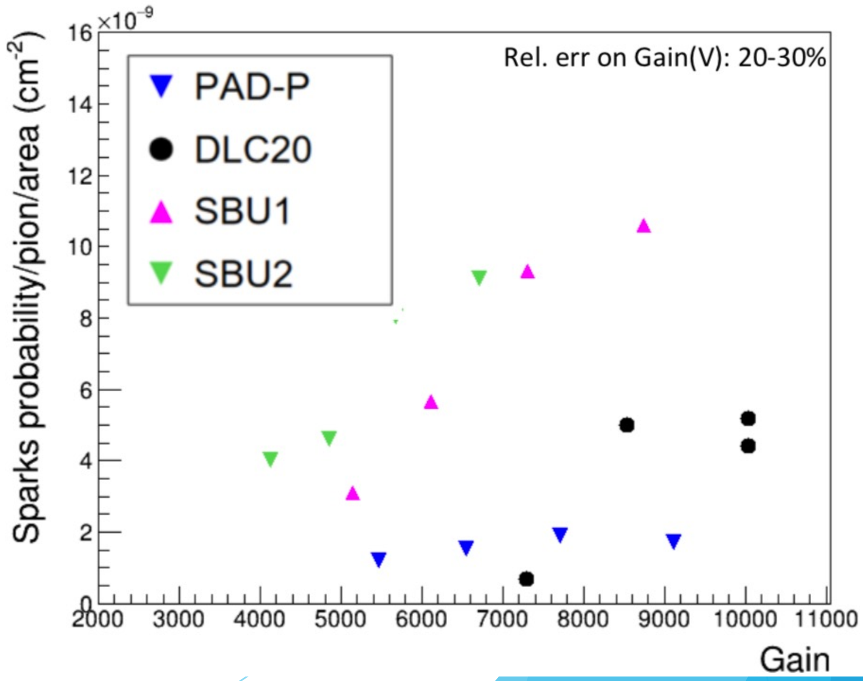
Test beam with 300 MeV/c pions @ PSI with a rate of ~0.1 MHz/cm^2 has been mainly devoted to study the sparks probability for different prototypes



- Gain measurements with pions are in good agreement with ^{55}Fe and Cu-target X-Rays measurements.
- With a gain greater than 7500 PAD-P is the more robust prototype.

We count as "a spark" any change in drawn current greater than 30%

Spark probability: $\frac{\#\text{ sparks}}{\text{Time window}\cdot\text{Area}\cdot\text{Particle rate}}$



Different resistive layouts comparison

The two different sparks suppression resistive layouts has been extensively studied during last years: Detector performances have been compared in similar conditions of Ar/CO_2 (93:7) gas mixture and of GAIN (~ 6500 –7000)

- **Spatial and Energy resolution:**
  - Best performance obtained with the **DLC20** prototype:
  - excellent spatial resolution due to larger charge spread over more pads (<100 μm on the precision coordinate);
  - Very good energy resolution <30% FWHM better than **PAD-P** due to the more uniform electric field (no pad edge effects).
- **Rate Capability:**
  - **PAD-P**: No dependence on the irradiated area, ~20% (< 530 V) gain drop at 20 MHz/cm2, gain drop is dominated by charging-up.
  - **DLC20**: Gain reduction is ~20% (< 520 V) at 20 MHz/cm^2 when the irradiated area has a surface of ~0.8 cm^2 (as PAD-P); it increases to ~30% for larger areas.
- **Discharge probability and robustness**
  - **PAD-P**: It is very stable up to gains >> 10^4; sparks prob <= $2 \cdot 10^{-9}$ /(pion · cm^2) in the investigated gain range.
  - **DLC20**: It is quite robust but not as well as PAD-P; sparks prob <= $5 \cdot 10^{-9}$ /(pion · cm^2) in the investigated gain range. F

Summary

- Several small-pad resistive micromegas prototypes, with different concepts of the spark protection resistive system, have been tested and compared.
- Prototypes with embedded electronics is built and under test.
- Wide R&D program still to be completed:
  - Evaluate new FE chips alternative to APV25;
  - Produce and test larger prototypes (20x20) cm^2 with embedded electronics;
  - Gas mixture optimization;
  - Ageing studies;
  - Detector simulation studies and resistive layout parameters optimization.

Aknowledgements and bibliography

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- R. De Oliveira, B. Mehl, O. Pizzirusso and A. Texeira (CERN EP-DT) for ideas, discussions and the construction of the detectors
- CERN RD51 Collaboration CERN GDD Lab for the continuous support during prototypes testing.

More significant publications and conference proceedings from our R&D:

- M. Alviggi et al., "*Construction and test of a Small-Pads Resistive Micromegas prototype*", JINST 13 (2018) no.11, P11019
- M. Iodice et al., "*Small-pad Resistive Micromegas: Comparison of patterned embedded resistors and DLC based spark protection systems*" J. Phys.: Conf. Ser. (2020) 1498 012028

R&D based on previous developments od Pad micromegas for COMPASS and for sampling calorimetry

- C. Adloff et al., "*Construction and test of a 1x1 m2 Micromegas chamber for sampling hadron calorimetry at future lepton colliders*" NIMA 729 (2013) 90–101.
- M. Chefdeville et al. "*Resistive Micromegas for sampling calorimetry, a study of charge-up effects*", Nucl. Inst. Meth. A 824 (2016) 510.
- F. Thibaud at al., "*Performance of large pixelised Micromegas detectors in the COMPASS environment*", JINST 9 (2014) C02005.

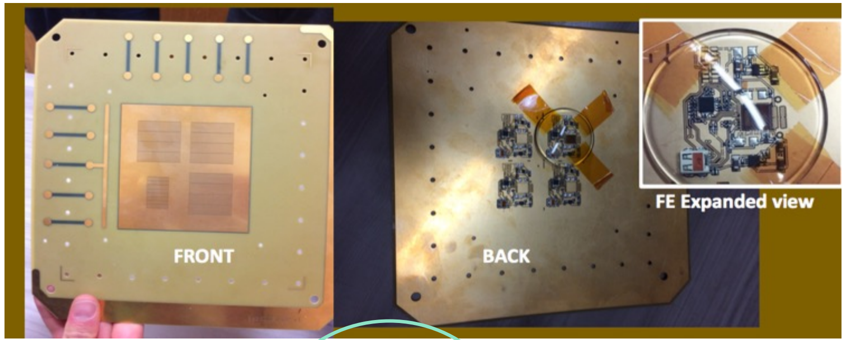
DLC double resistive layer configuration re-arranged from μ-RWell R&D:

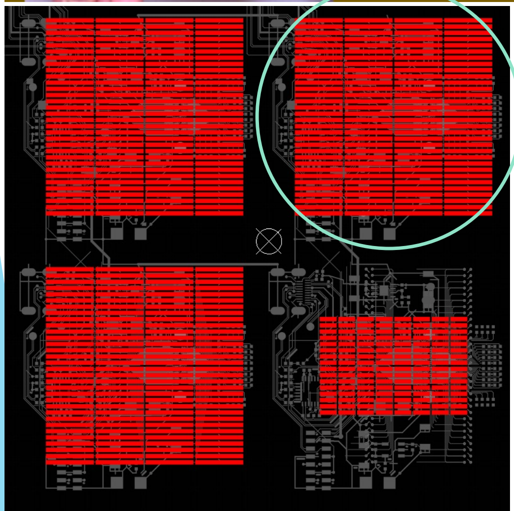
- G. Bencivenni et al., "The micro-Resistive WELL detector: a compact spark-protected single amplification- stage MPGD" 2015 JINST 10 P02008
- G. Bencivenni et al., "The μ-RWELL layouts for high particle rate" 2019 JINST 14 P05014

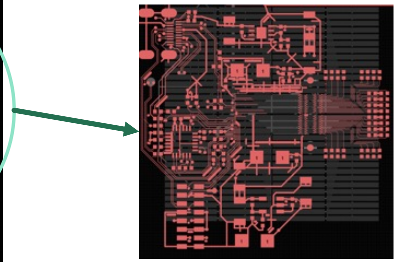
Backup slides

Next Step: the prototype with Integrated Electronics

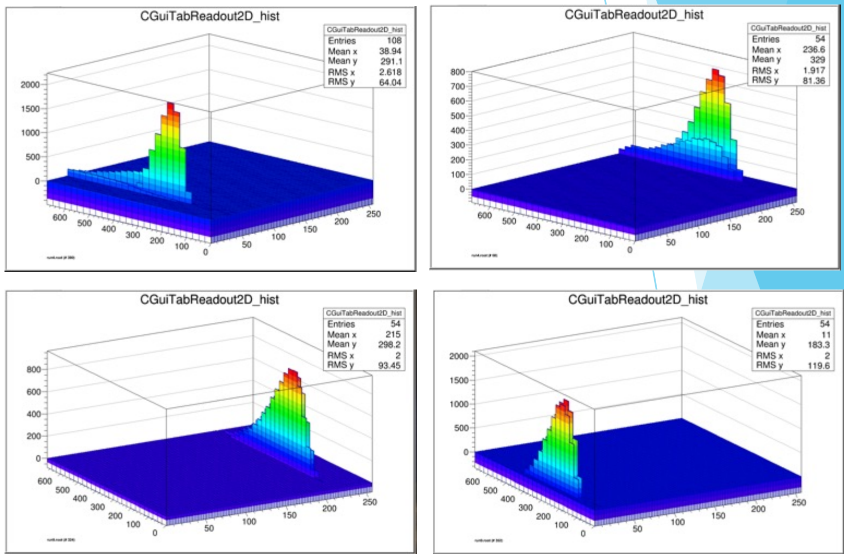
- In order to solve the problem of the signal routing when scaling to larger surface prototypes with integrated electronics on the back-end of the anode PCB have been built.
- APV FE chip used for the proof-of-concept: looking for alternative and more suitable solutions







APV FE chip layout



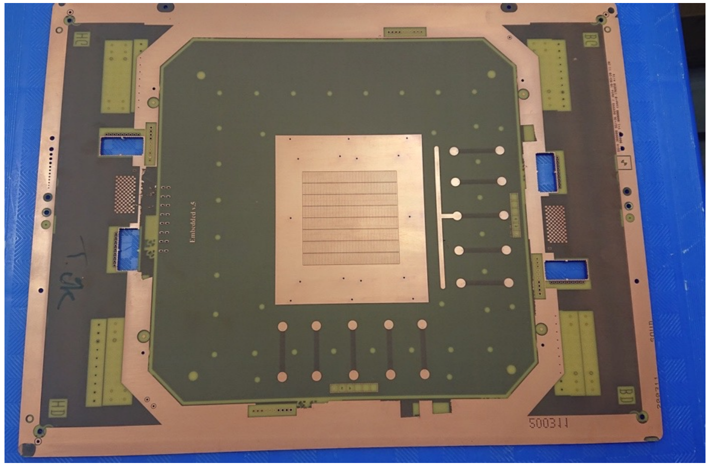
First tests promising:

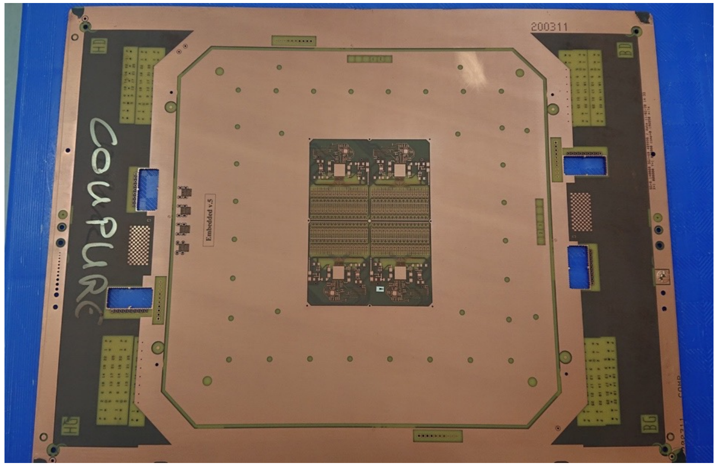
- Nice Pedestals structure and signal response from APV using ^{55}Fe source and random trigger for DAQ → **BUT ONLY on some channels**
- Reason understood (issue in the elx Layout)
  → **fixed it in the next prototype !**

Next Step: the prototype with Integrated Electronics

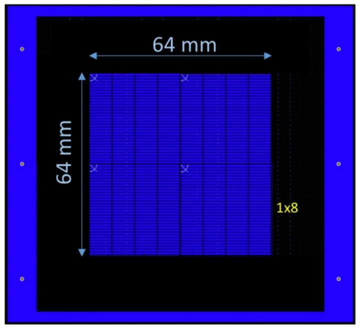
- In order to solve the problem of the signal routing when scaling to larger surface prototypes with integrated electronics on the back-end of the anode PCB have been built.
- APV FE chip used for the proof-of-concept: looking for alternative and more suitable solutions

FRONT VIEW





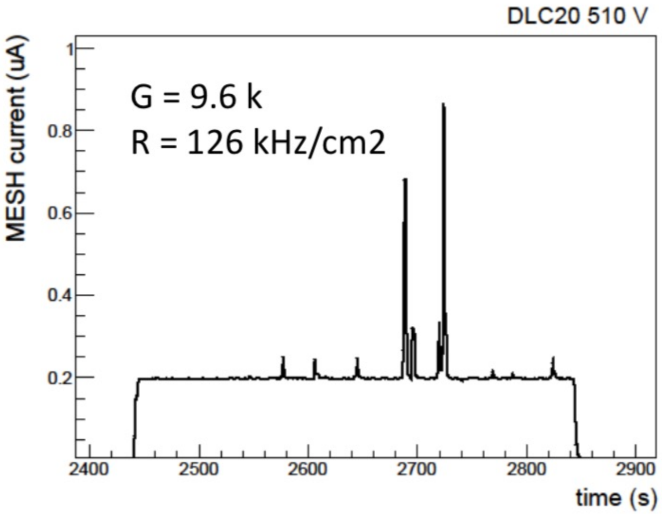
BACK VIEW

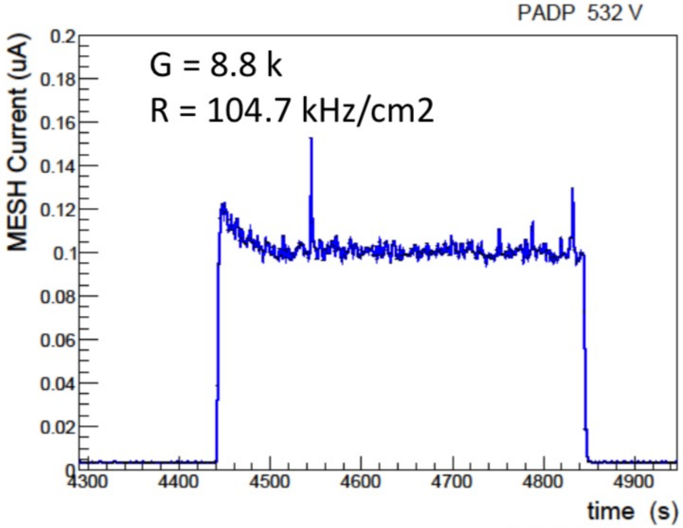


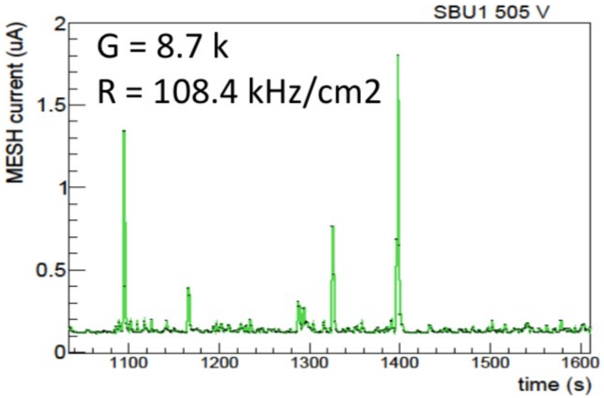
New prototype delivered at the end of March 2020

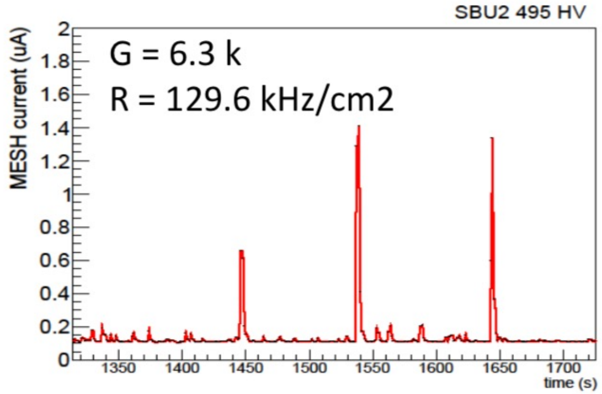
- Readout pad matrix changed to 512 pads for an active surface of 6.4 x 6.4 cm^2 to reduce costs.
- Detectors assembled during summer 2020
- Tests will be performed during fall 2020

Example of spark events

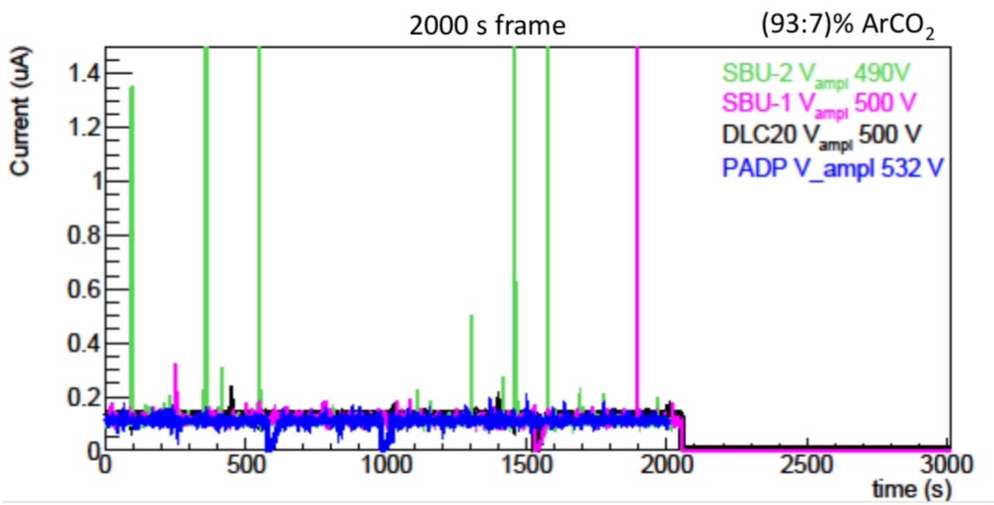


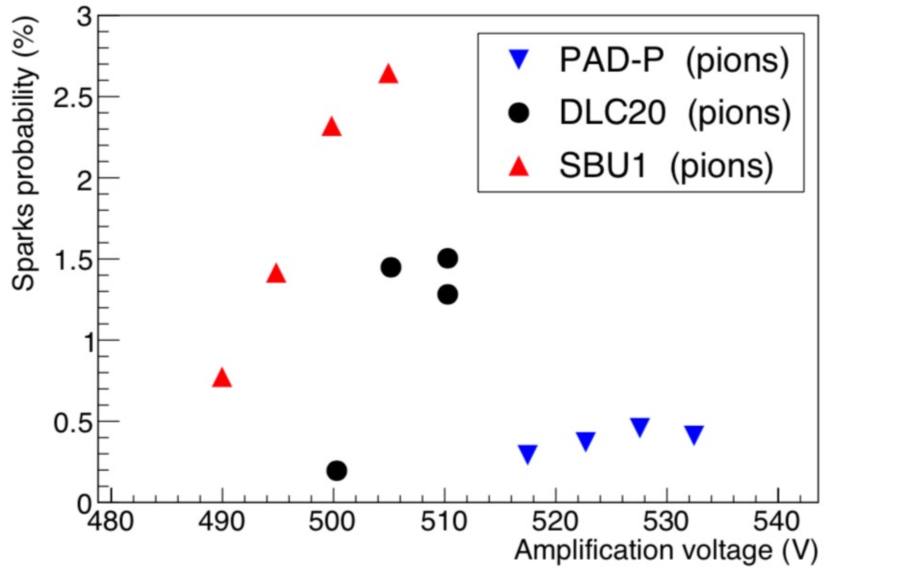




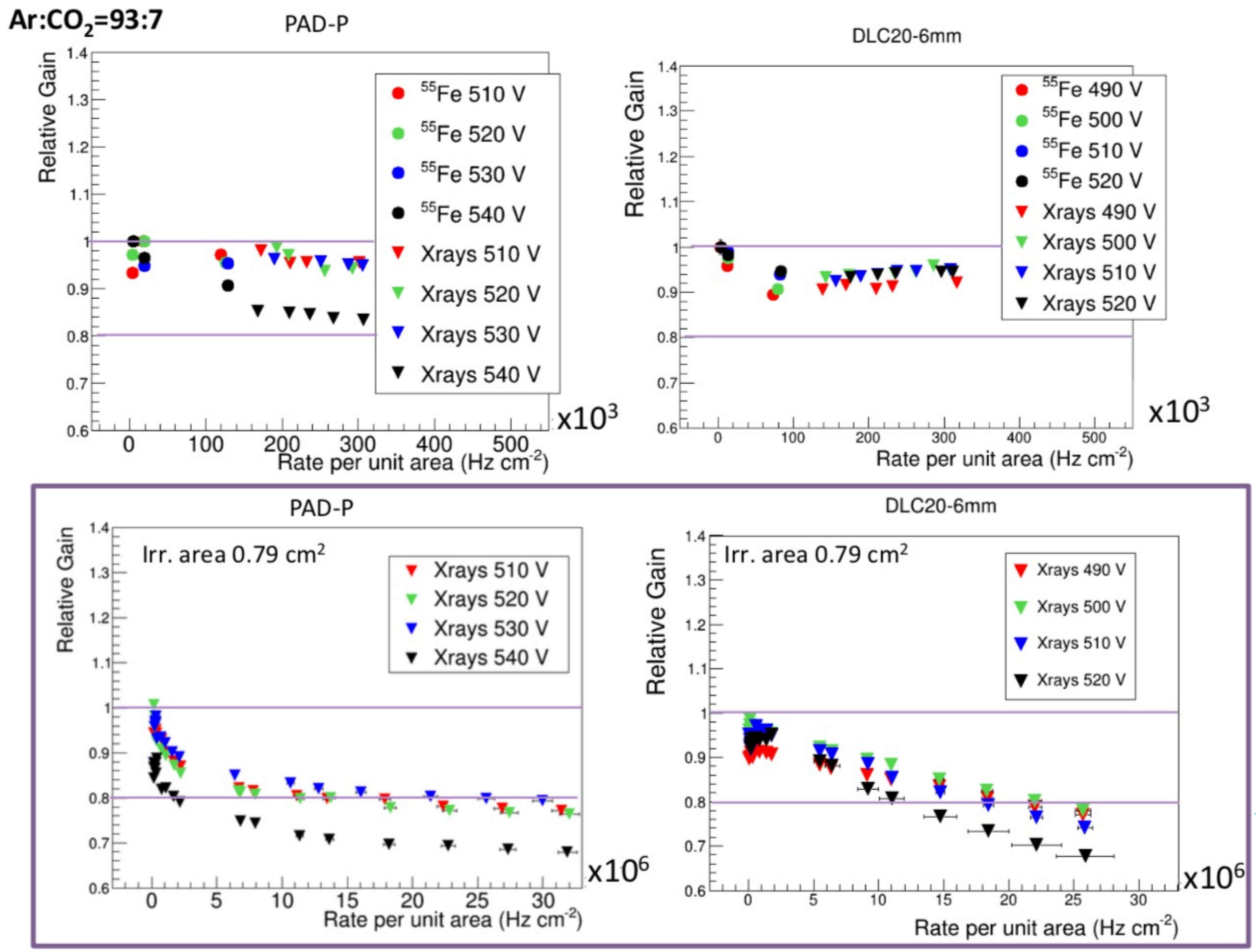


Discharge studies @ PSI

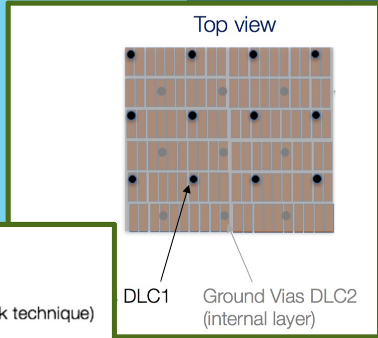




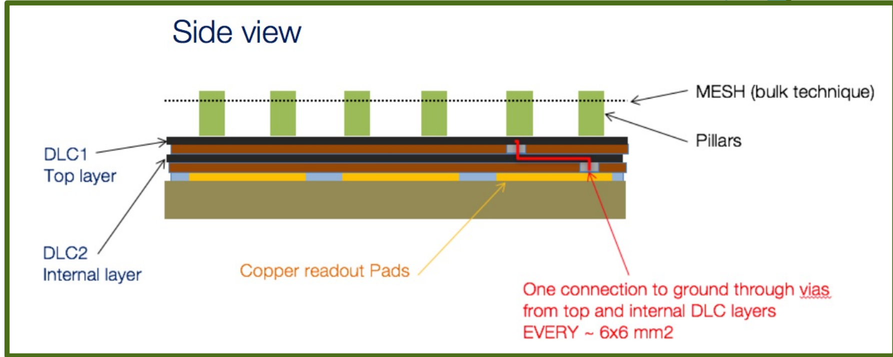
Rate capability at different rates

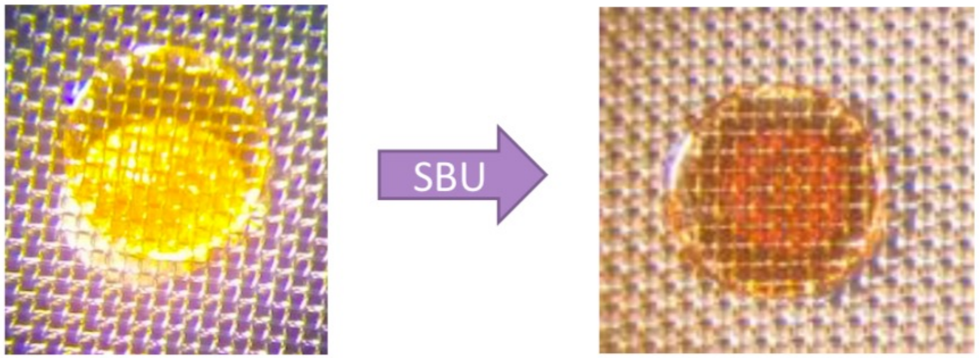


Technological improvement of DLC prototypes
(SBU - Sequential Build Up - scheme 2)



- During the characterization studies of DLC prototypes, a non perfect alignment between vias and pillars in construction process was found, resulting in a larger discharge probability:
- New Sequential Build Up (SBU) technique: Improvement in building the vias in the DLC foils (using copper cladded DLC foils) and of the precision of vias covering with pillars.

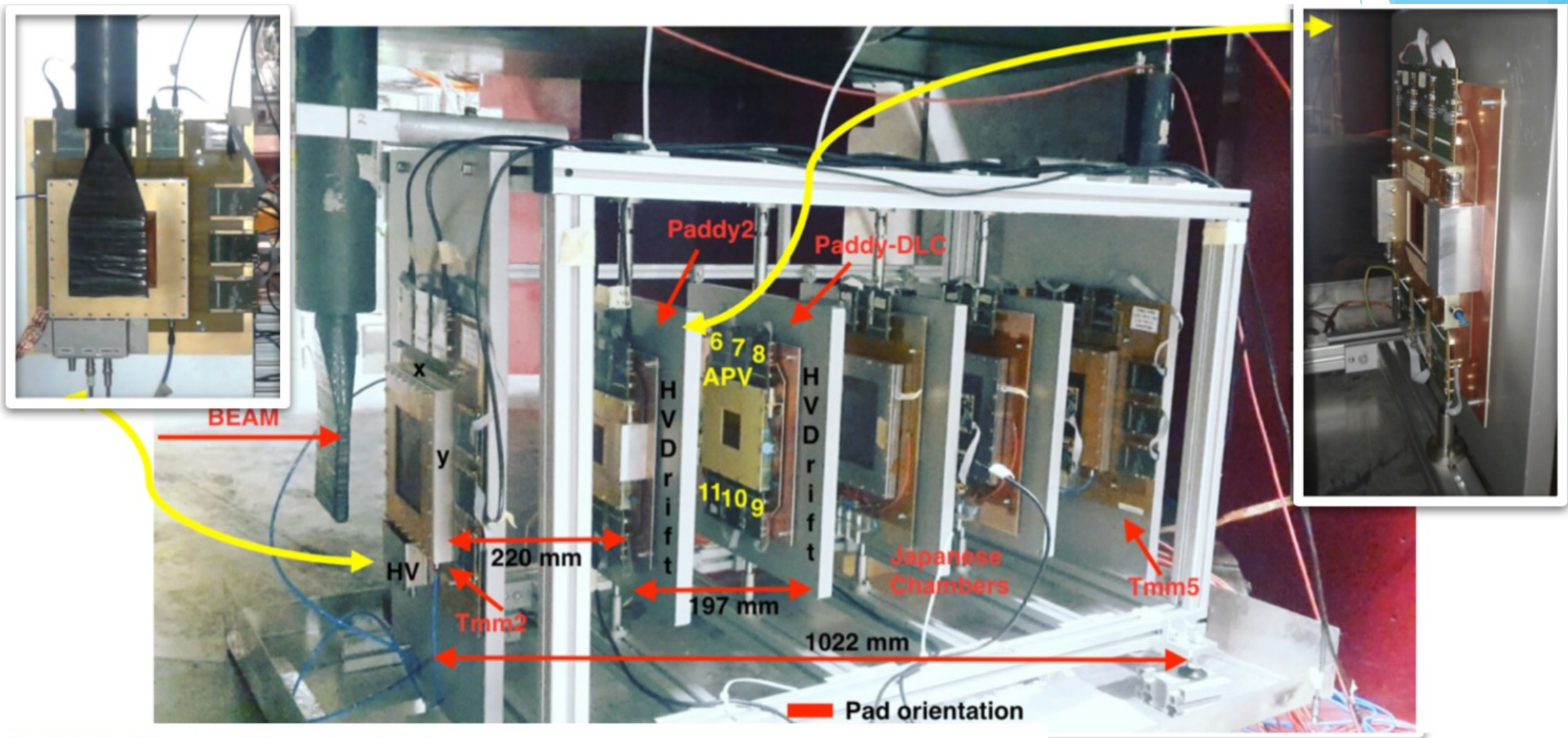




Different prototypes built with DLC/SBU technique

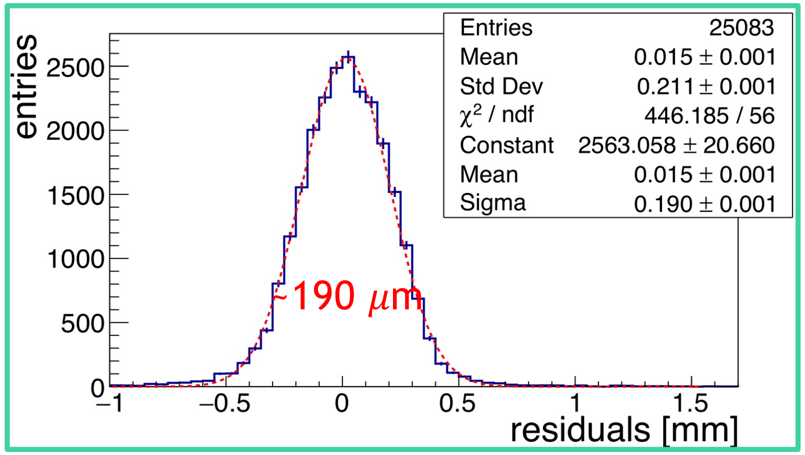
1. **DLC50:** high resistivity 50-60 MΩ/sq DLC foils;
   6 mm vias pitch side and 12 mm vias pitch side;
2. **DLC20:** low resistivity 20 M Ω /sq DLC foils;
   6 mm vias pitch side and 12 mm vias pitch side;
3. **SBU1:** combination of DLC foils with 5 MΩ/sq and 35MΩ/sq resistivity, implemented with SBU technique; 6 mm vias pitch in the entire plane;
4. **SBU2:** copy of SBU1.

Test beam Setup in 2017

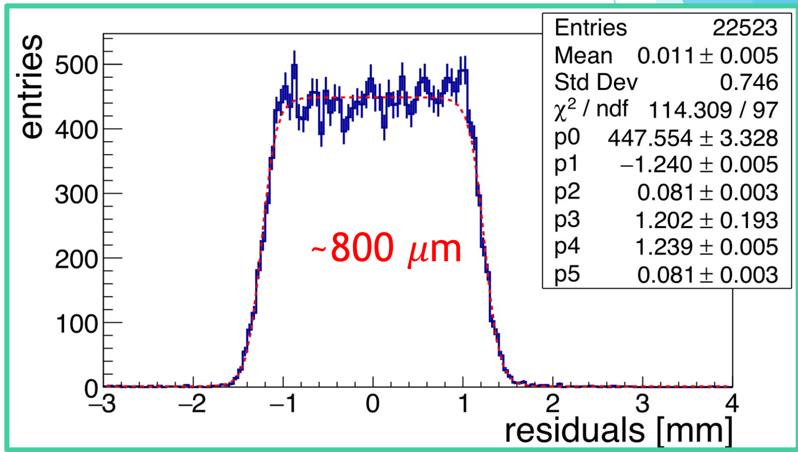


Spatial resolution for PAD-P in TB 2016

Precision coordinate (1mm pitch)

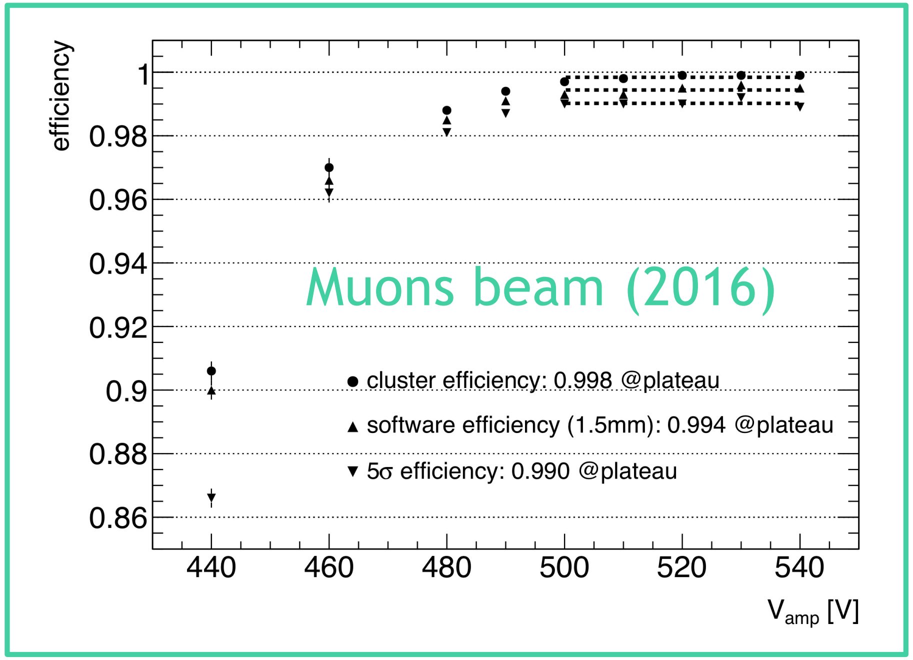


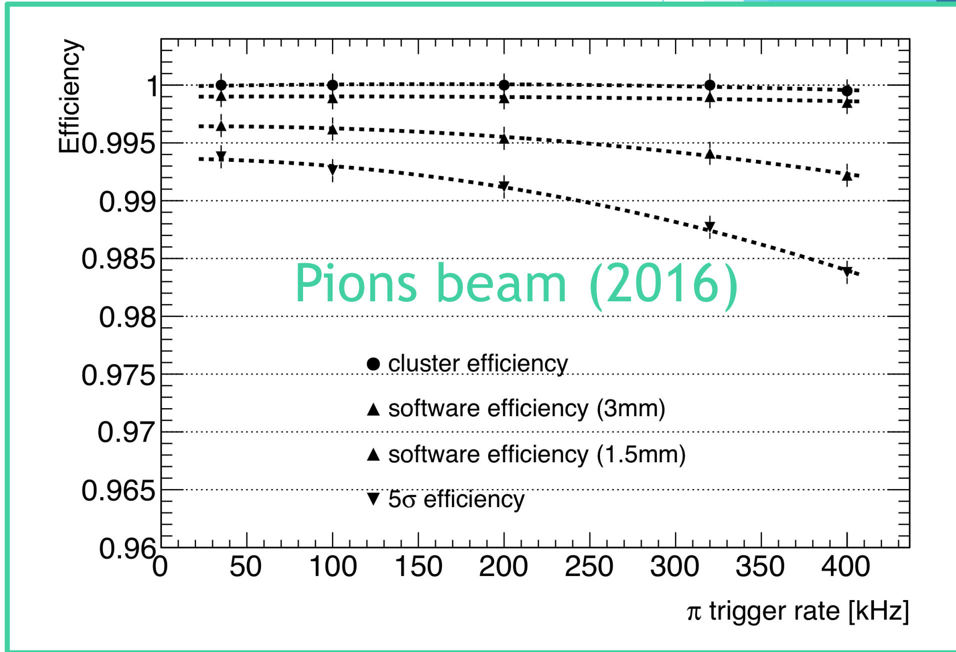
Secondary coordinate (3mm pitch)



Efficiency for PAD-P prototype in TB 2016

- Efficiency greater than 99% for muons and still above 98% for high energy pions up to a trigger rate of 400 MHz, corresponding to a pion rate of few MHz/cm2 in the middle of the pion beam spot

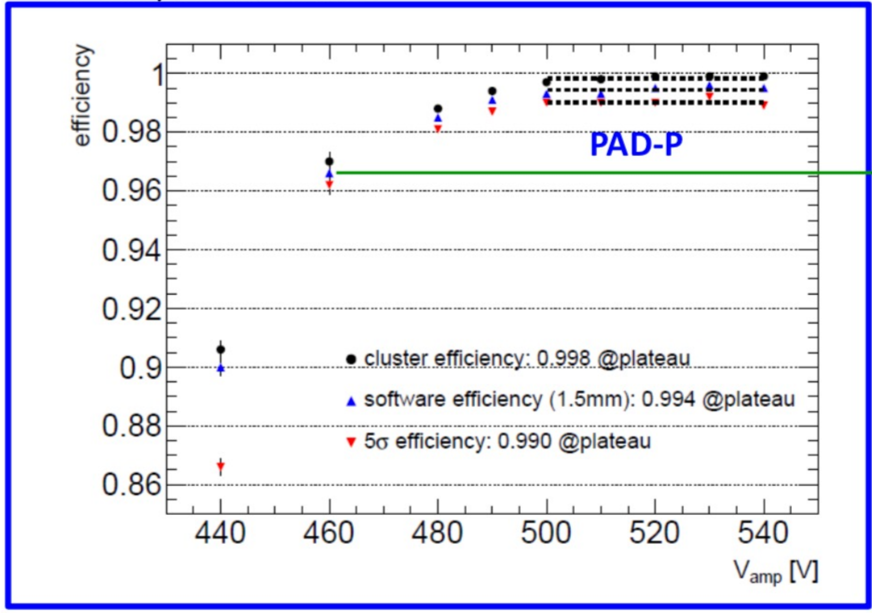


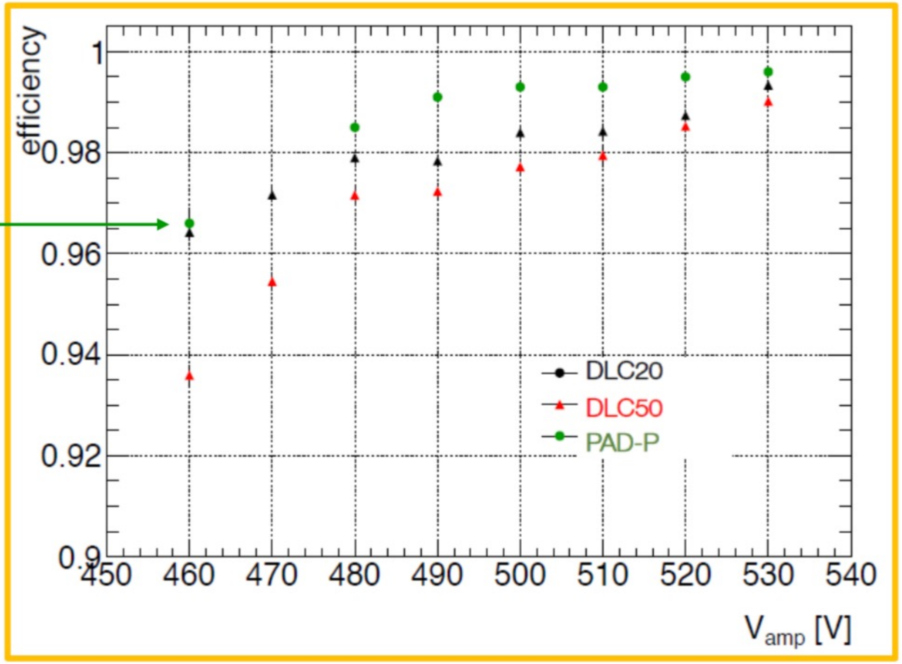


Efficiency for DLC prototypes at TB 2017

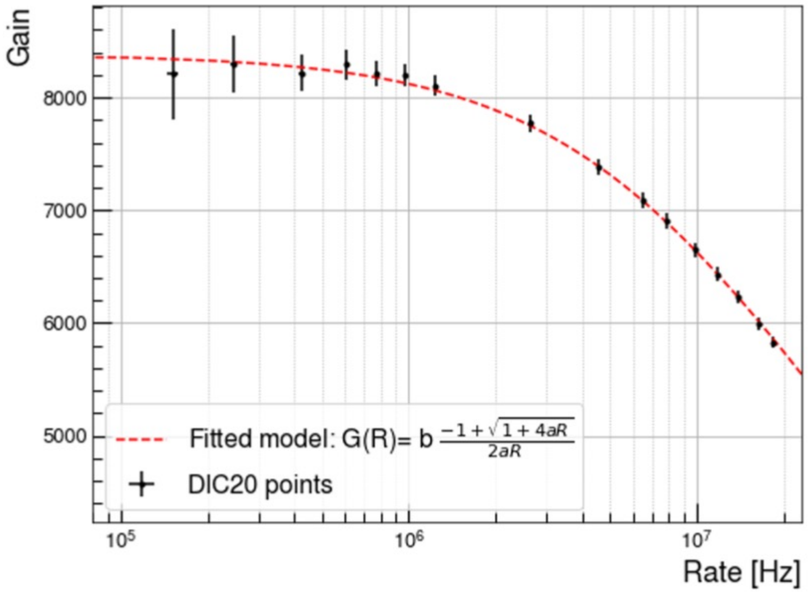
The DLC prototypes did not show clear plateau regions in the **efficiencies** as the PAD-P layout, for which the cluster efficiency is~ **99.8%,** the 1.0 mm tracking efficiency is~ **99.0%** and the 1.5 mm tracking efficiency is~ **99.4%** at plateau regions.

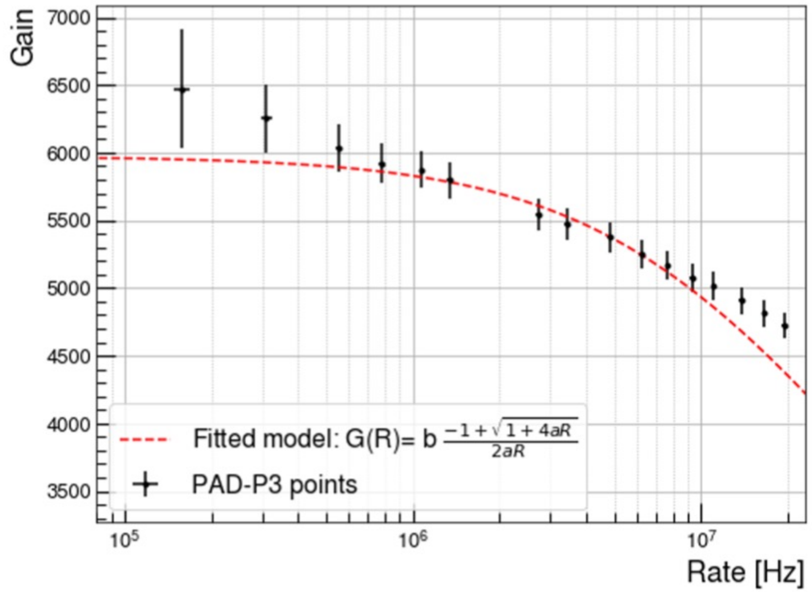
~ 100 GeV/c muon beam





Gain ohmic drop @ very high rates





Fit attempted with the model in **G. Bencivenni et al. 2015 JINST 10 P02008** considering a Ohmic drop

- Fit in good agreement with data for DLC20
- Fit failure on Paddy3 as expected due to the different contribution to the drop (charging-up)

Charging – up with Xrays

- Test to probe effects of charging up on Pad-P3 ramping up and down I_{xray}, successive measures taken within short period of time (but the whole measure lasted > 3 hours)
- No strong effects of charging-up seen on DLC20