Resistive MPGD
Processes and problems

Rui de Oliveira 12/02/2020

CERN RD51 mini-week

Goal of resistive protections

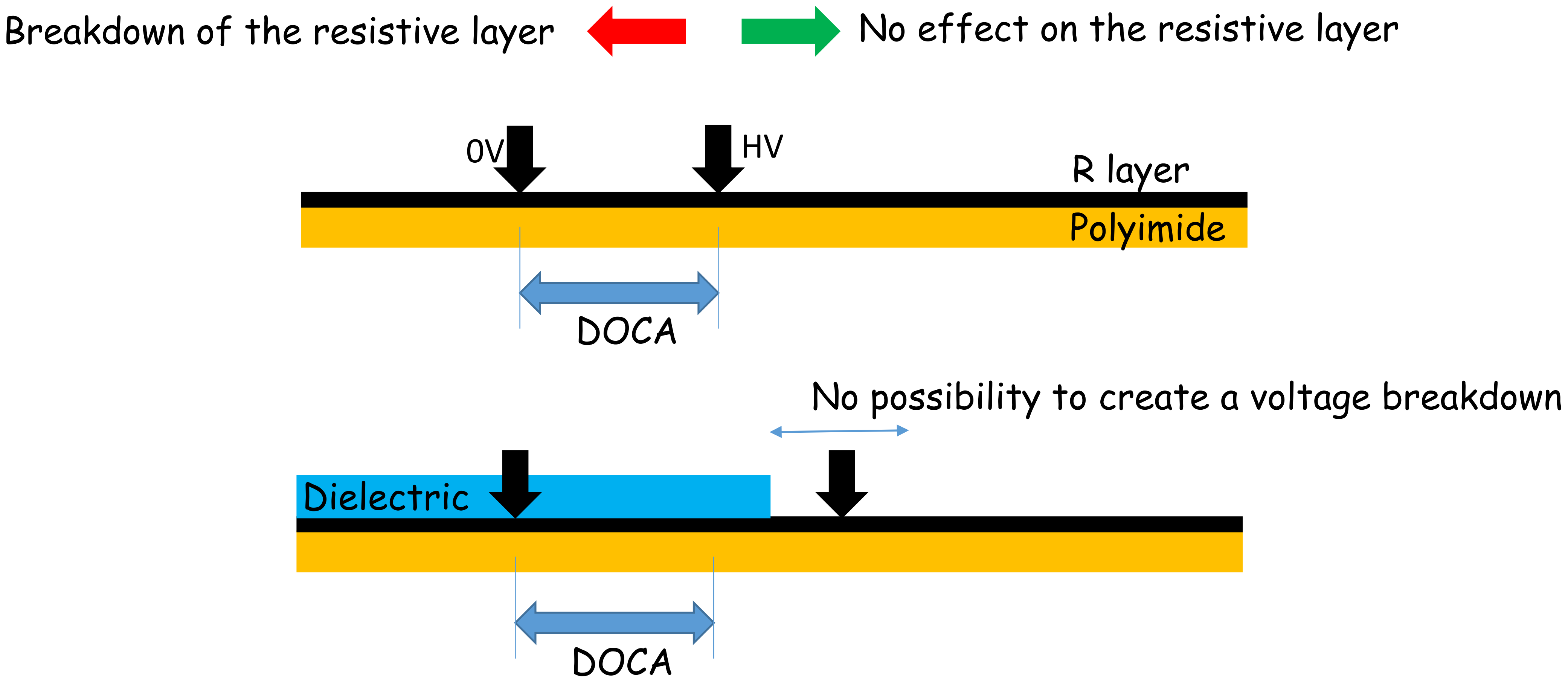
- Make Sparks invisible
- Simplify the detector structure
- Reduce the cost
- Be large size compatible
- Aim to use only industrial processes
- Achieve performances competitive with best existing MPGDs
    - Rate
    - Space resolution
    - Time resolution
    - Energy resolution
    - Low mass

Type of resistive MPGDs

- Resistive Micro-Megas
    - Single resistive layer
    - 2 resistive layer
- Micro-Resistive-Well
    - Single resistive layer
    - 2 resistive layer protection
- Resistive GEM
- Resistive THGEM

DOCA

(Distance Of Closest Approach)



Breakdown of the resistive layer

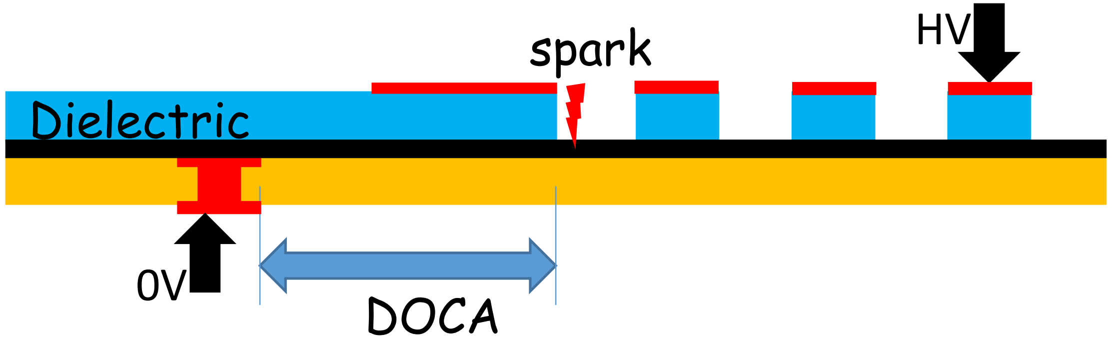
No effect on the resistive layer

No possibility to create a voltage breakdown

A breakdown of the resistive layer means creating a low Ohmic channel in the layer

DOCA

(Distance Of Closest Approach)



The most critical damage in this protection system is the resistive material breakdown due to the voltage set by the spark.

- -This BV is an intrinsic parameter of resistive material.
- -Setting a good DOCA can prevent any breakdown of the resistive layer.
- -This is first barrier , if it fails there is no control on the spark current .

Breakdown voltage

PI	420MV/m
DLC theory	650MV/m
our measurement	10MV/m
Perfect SiO2	1000MV/m
PVD SiO2	1MV/m

Of course, dielectric strength are greatly impacted by impurities, dopants, structure, interconnected porosity, flaws and micro-cracks from thermal expansion mismatches

If DOCA is set correctly, the next damage (current instabilities) will come from electron/ion bombardment→

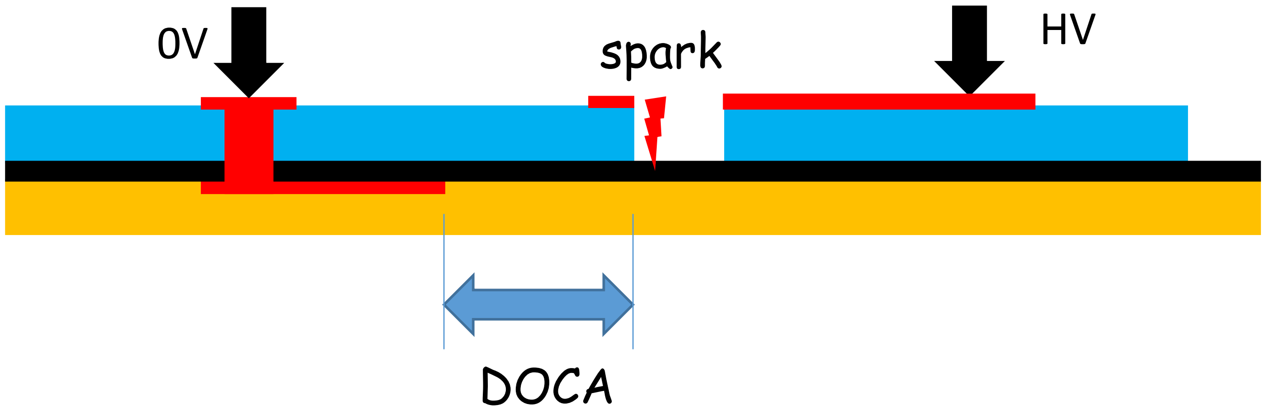
- temperature rising (joule effect) →material evaporation →material deposition

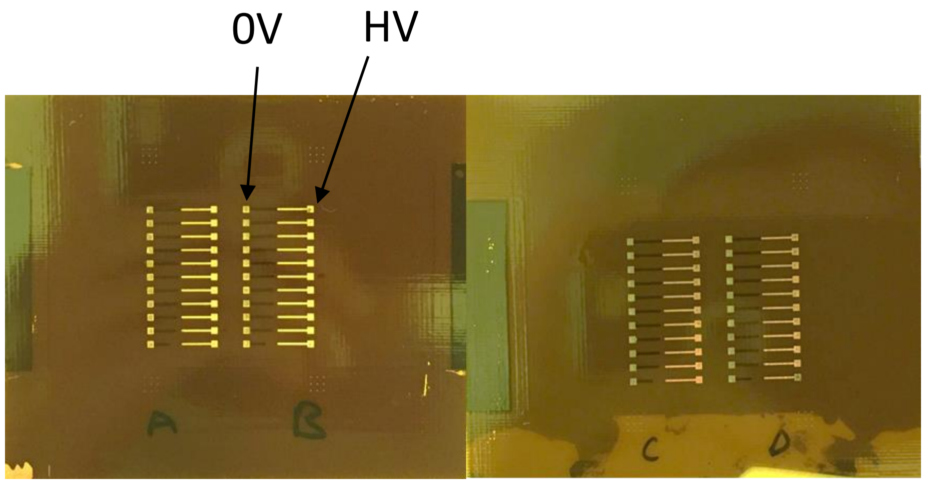
This effect can be reduced:

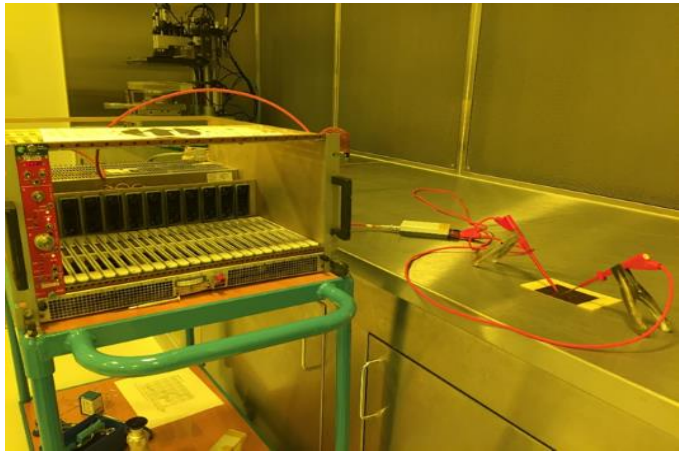
- -firstly by far, avoiding local repetitive sparks → get rid of contaminants like dust.
- -by increasing the melting point of materials → higher the better for protection
- -by increasing the thermal conductivity of materials → good thermal conductors & thicker layers
- -by reducing the amount of charges induced by the spark→ by increasing the resistive value

Material	Thermal conductivity W/mK
Glass epoxy	0.2
PI	0.18
Aluminium	235
Copper	384
Natural diamond	895–1350

DOCA test



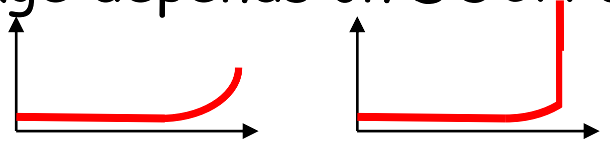




- 11 patterns → DOCA ranging from 1.0mm down to 0.1 mm
- Single hole test
- DLC 60M/Sqr
- 4 sets have been tested (A,B,C,D)

Discussion on DOCA

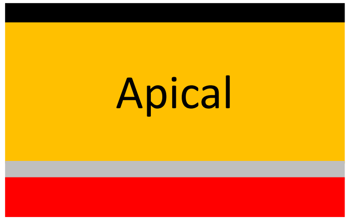
- First observation, the voltage to see current is close to 800V in air!
  - We were expecting 650V for a 50um gap (like GEMs)
- Second ,the current shape during overvoltage depends on DOCA distance
  - Smooth current increase with long DOCA
  - sudden increase to uA with small DOCA



- After 30 sec with 30nA in one hole we can observe a voltage drop
  - After several session of 30s , it stabilize in between 550V to 650V (0 current voltage)
  - No voltage breakdown , no visible damages on any structures.
- We want to look now at the "sparks" nature when operating in overvoltage mode.
  - We would like to study the single hole spark current shape and rate with a fast oscilloscope .
  - This is possible with DLC since we do not damage the device
- Preliminary results : with 60Mohms/Sqr DLC , the DOCA can be as low as 0.1mm without visible damages

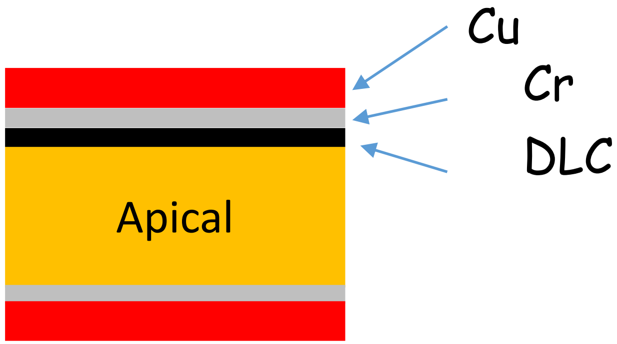
DLC naming

DLC



or

“DLC+”



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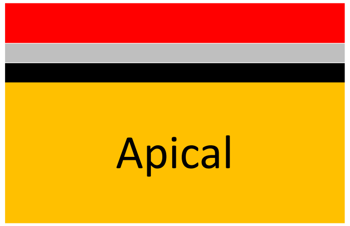
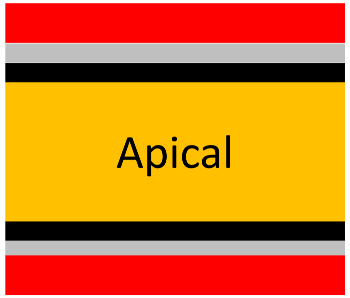
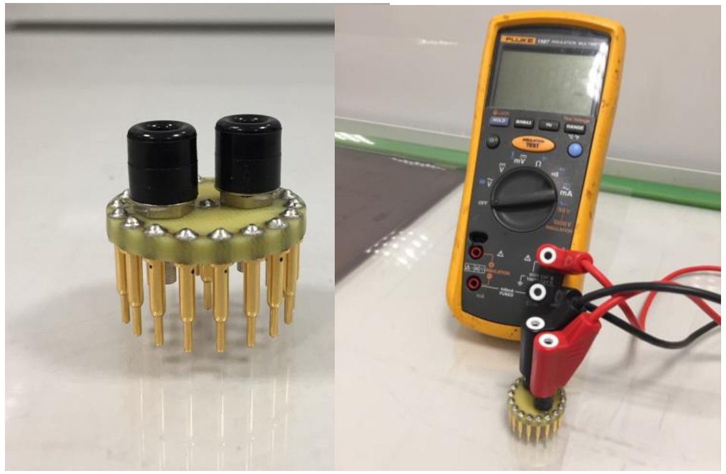
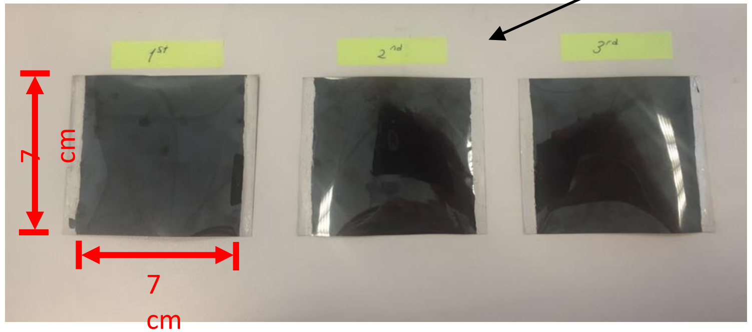


“DLC++”



Resistive measurements
Probe calibration



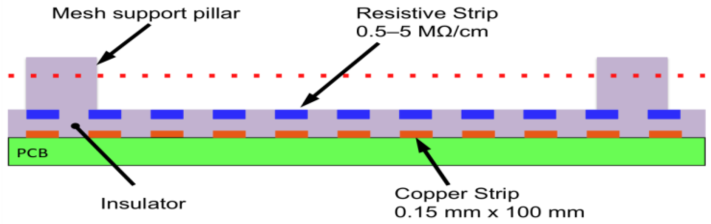


- 7cm x 7cm square of DLC
  - lateral silver connection to create 1 Square
- Connect probe to Ohm-meter
- Compare probe measurement to silver connections measurement
- Error in the range of 5%
- We can directly read the value from the Ohm-meter

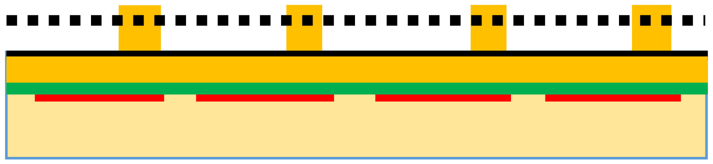
DLC Film	Surface Resistivity (kΩ/□)	Surface Resistance From The Probe (kΩ)	Coefficient Factor	Error (%)
1	359	345	1.041	4
2	386	364	1.060	6
3	403	380	1.061	5

Different Resistive protection approach with Micro-Megas

Medium rate detectors



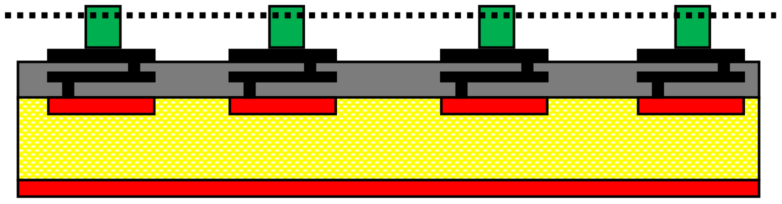
- Single layer screen printed



- 1 DLC

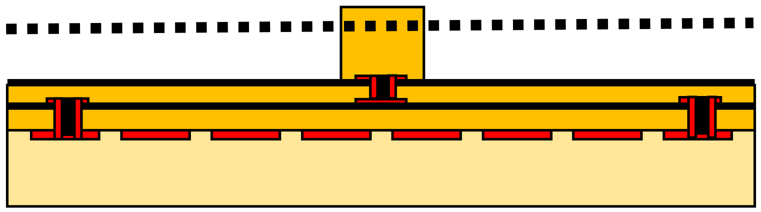
High rate detectors

Printed



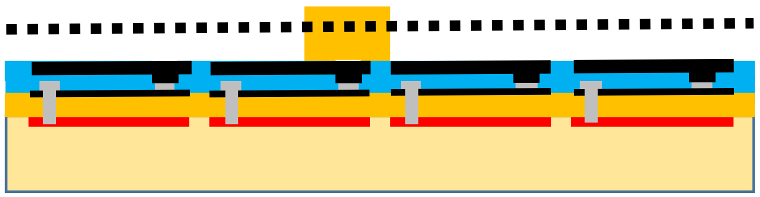
- 2 layers screen printed resistors

SBU



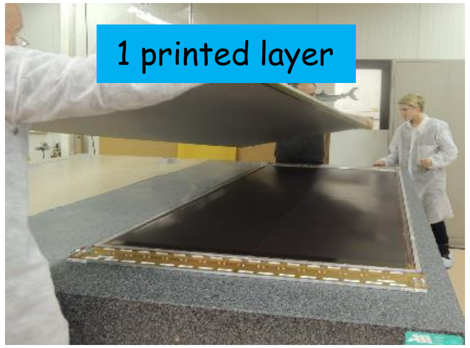
- 2 “DLC+” layers → SBU

Mix

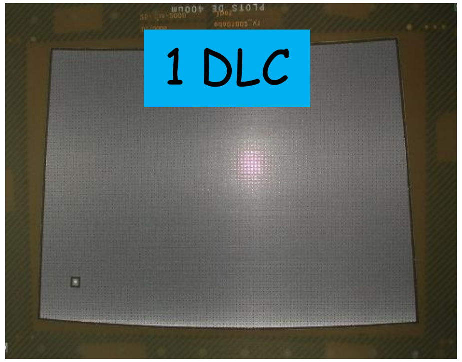


- MIX DLC and screen printed

Resistive Micromegas:

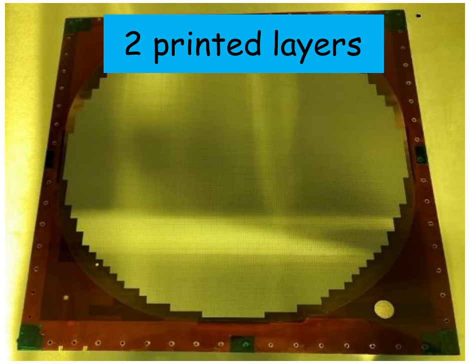


ATLAS NSW
Strips 100k/Sqr
2m x 1m

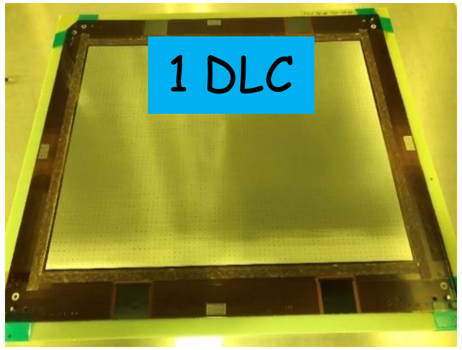


ILC TPC
30cm x 15cm
3mm x 8mm pads
2M/Sqr sharing layer

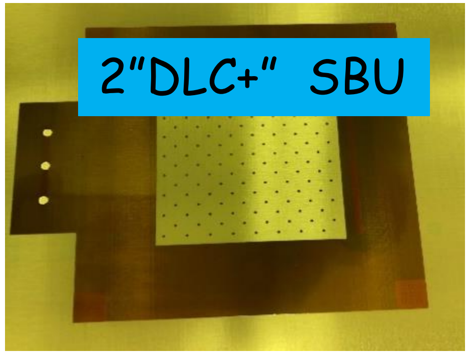
20 LSBB
50cm x 50cm
X/Y 1mm/1mm
30M/Sqr sharing layer



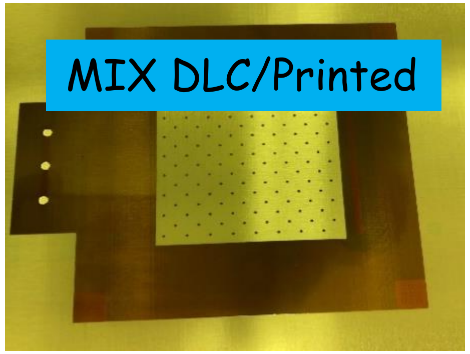
5 ILC DHCAL
50cm diameter
pads 1cm x 1cm
5M/Pad



32 T2K upgrade
40cm x40cm
1cm x 1cm pads
500K/Sqr sharing layer



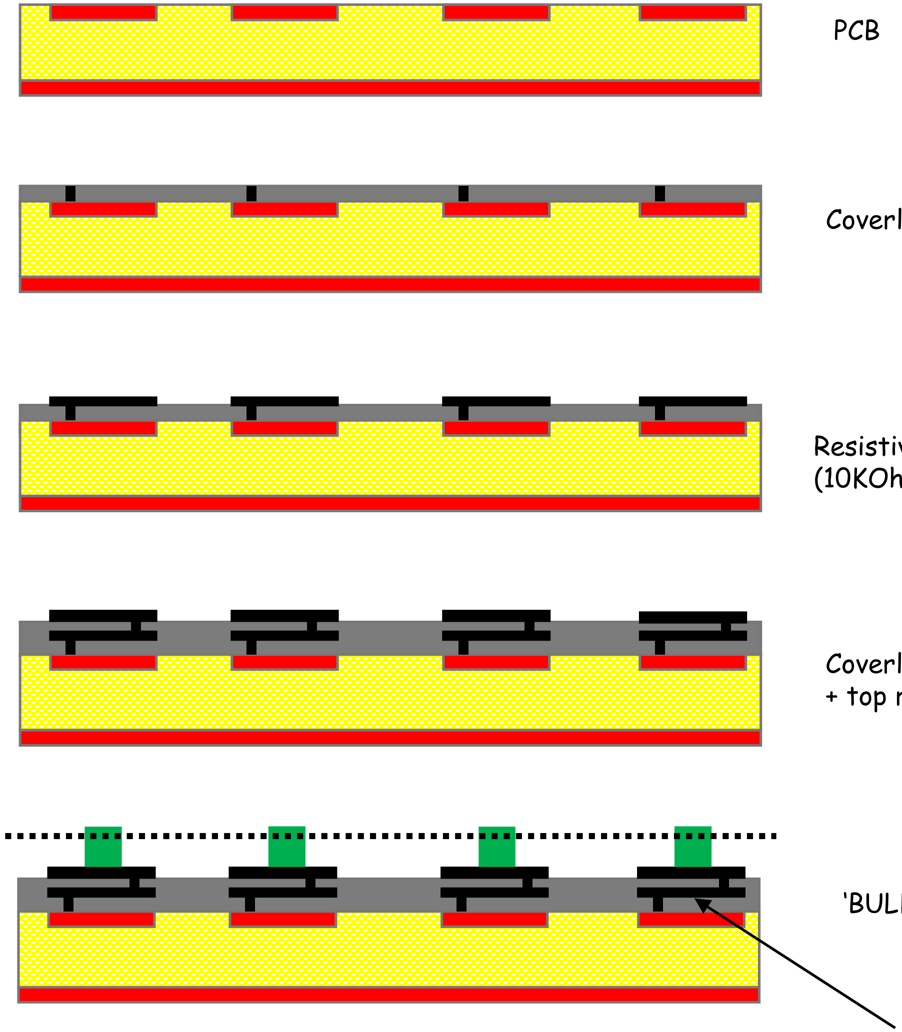
1 Demonstrator
5cm x 5cm
1mm x 3mm pads
2R layers 30M/sqr



2 Demonstrators
5cm x 5cm
pads 1mm x 3mm
5 and 20M/pad

2 Printed layers

-Extra Large DOCA
-Embedded Res should be less than 10KOhms/square
-Large pads
-Accurate layers registration even in large size
-No DLC needed
-High rate detectors


PCB

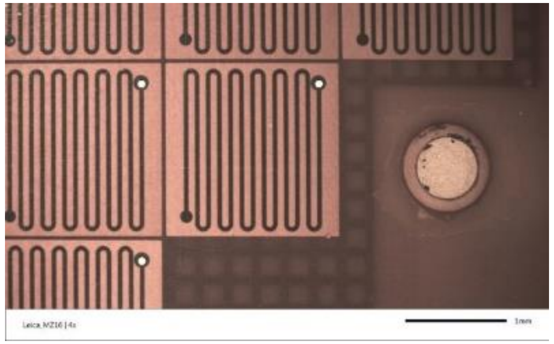
Coverlay gluing + drilling + via fill

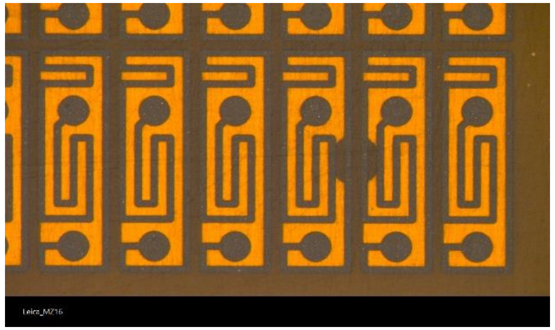
Resistive paste resistors
(10KOhms/square max)

Coverlay gluing + via fill
+ top resistive printing (100K max)

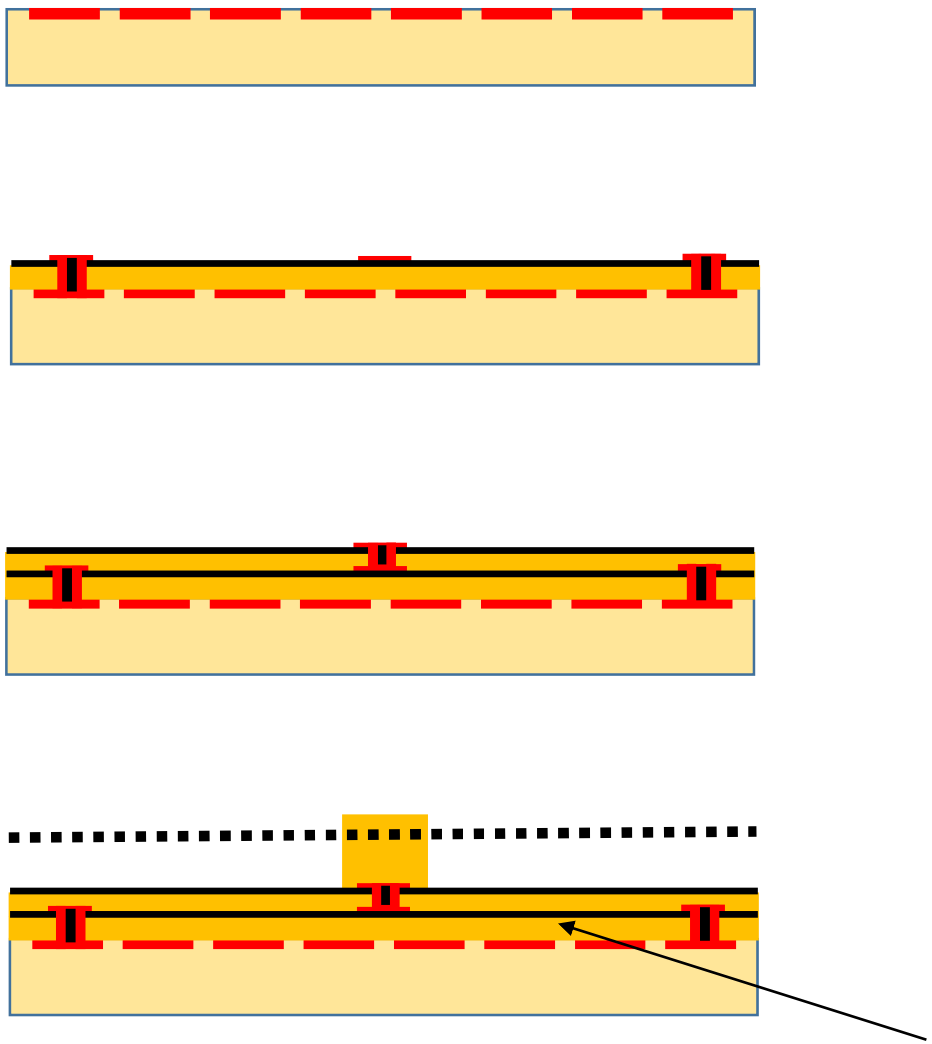
'BULKage'

DOCA: 10mm


1cm x 1cm pad→ Ok
There is space to create
2 to 20 Mohms Resistor
with 10K/sqr paste


1mm x 3mm pad→ Bad result
There is no space to create
2 to 20 Mohms Resistor
with 10k paste

2 “DLC+” structure with SBU process
Sequential Build Up


PCB

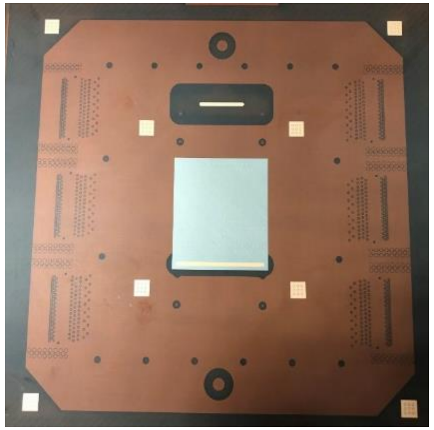
Glue “DLC+”
drill
Plate
Pattern Cu

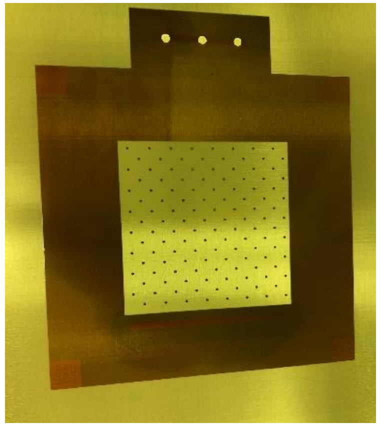
Glue “DLC+”
drill
Plate
Pattern Cu

‘BULKage’

DOCA: 3mm

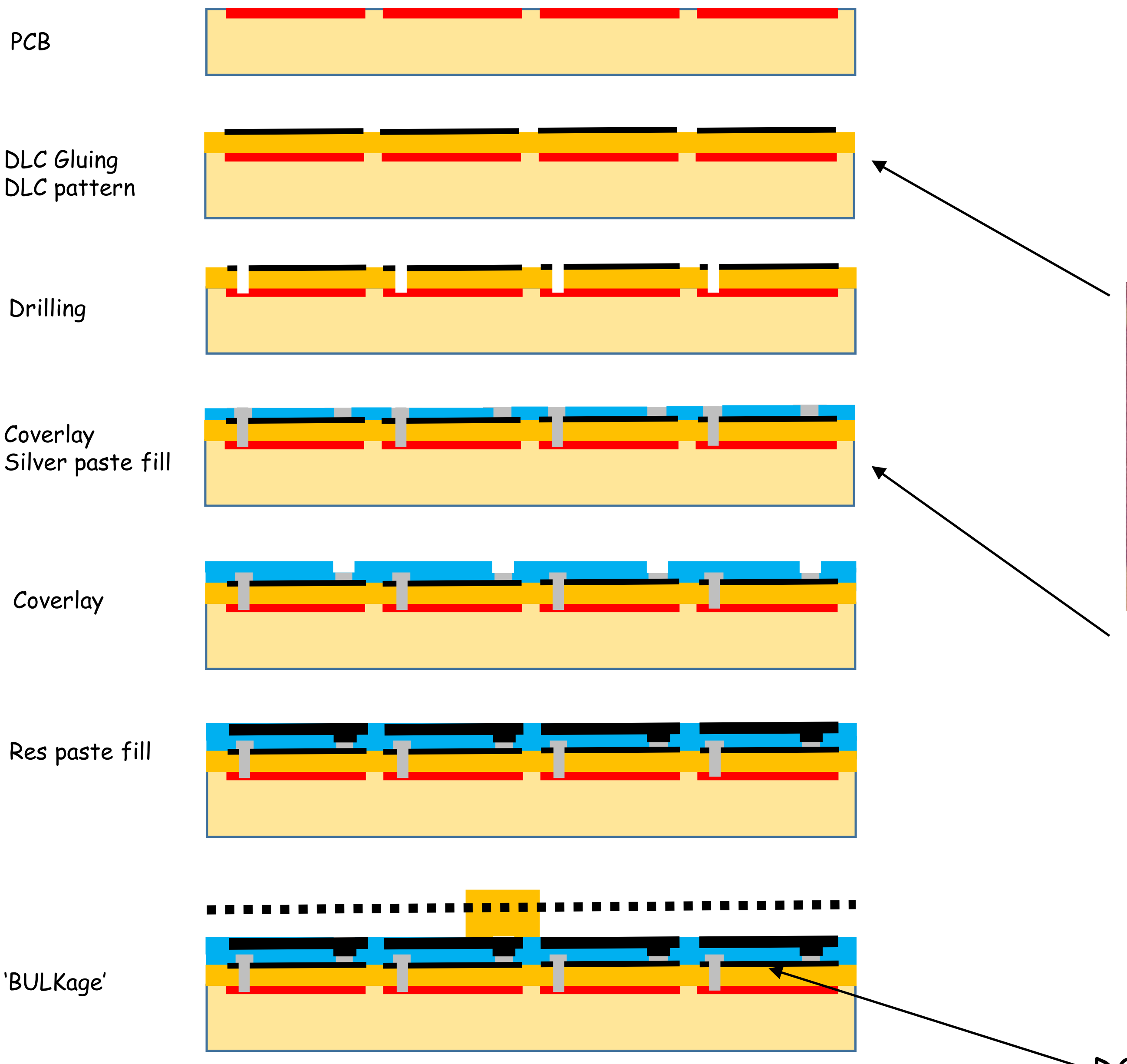
- -Extra Large DOCA
- -any resistive value
- -Adjustable evacuation point density VS rate
- -No major resistive change during production
- -Needs “DLC+”
  - -delamination
  - -resistive value
  - -DLC value hidden during processing
- -no problem with layers registration
- -good energy resolution
- -100% compatible with STD PCB processes

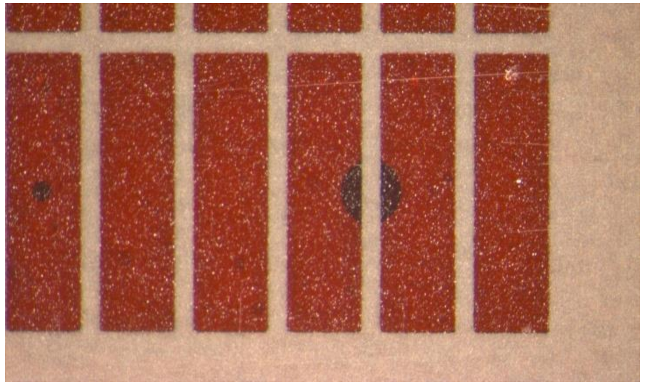


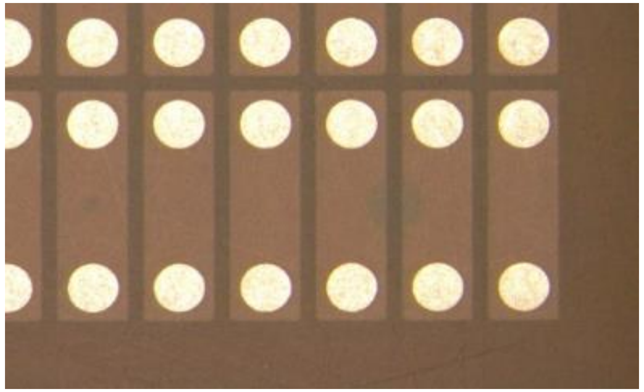


MIX method

- -Large DOCA
- -Any resistive value
- -Maximized evacuation point location
- -No major resistive change during production
- -Needs simple DLC foils
- -no problem with large size layers registration
- -the filling technic is not STD in PCB world
- -Ultra high rate detectors







Summary on R-MM

- We have now solutions for :
    - Large signal spreading
    - High rate
    - Small pads
    - Large size

- We need to improve the DLC/Cr/Cu deposit to propose a solution 100% compatible with industry (out of the BULK process).

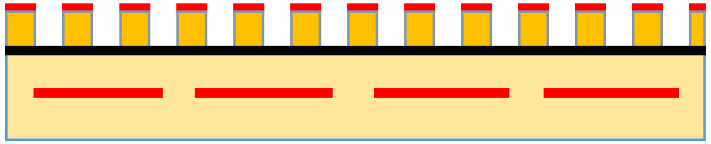
- We need also to work on the DLC resistive value prediction with “DLC+” materials

- Resistive detectors need better cleanliness during production than STD ones

- DLC can be patterned

Different Resistive protection in μRwell

μRwell



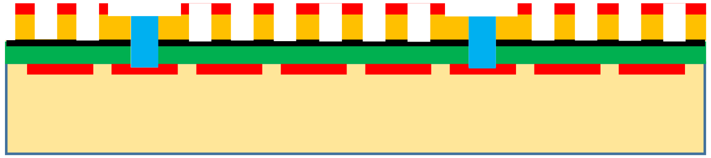
- Single DLC layer

High rate detectors

SG

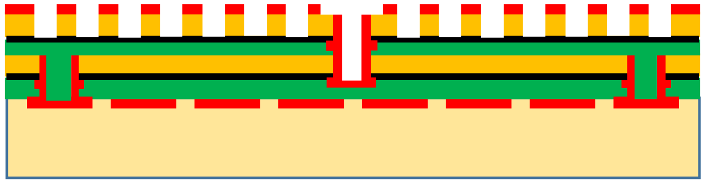
- 1"DLC+" with Silver or Cu evacuation Grid

DF



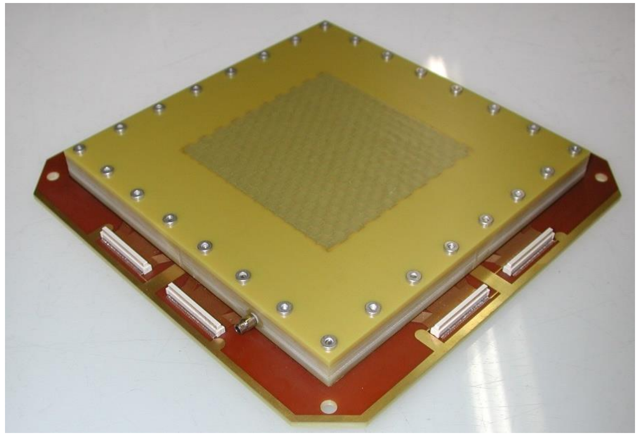
- 1 DLC with Drill and fill method

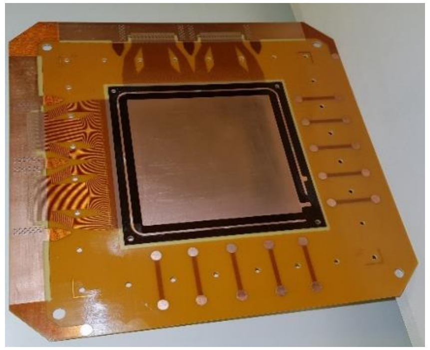
SBU



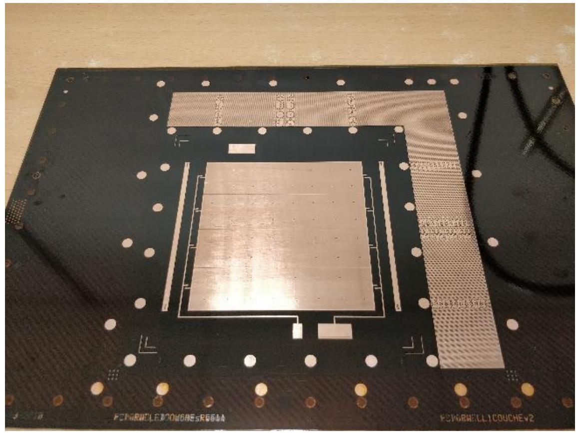
- 2 "DLC+" Sequential Build Up

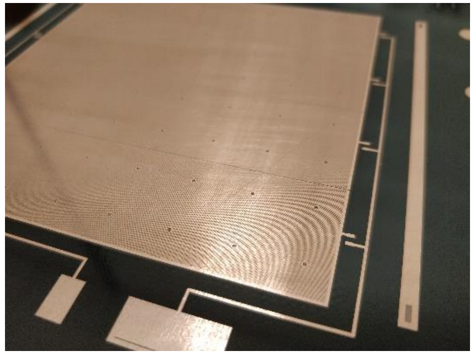
µRwells examples :





10cm x 10cm
µRwell detector
“study kit”

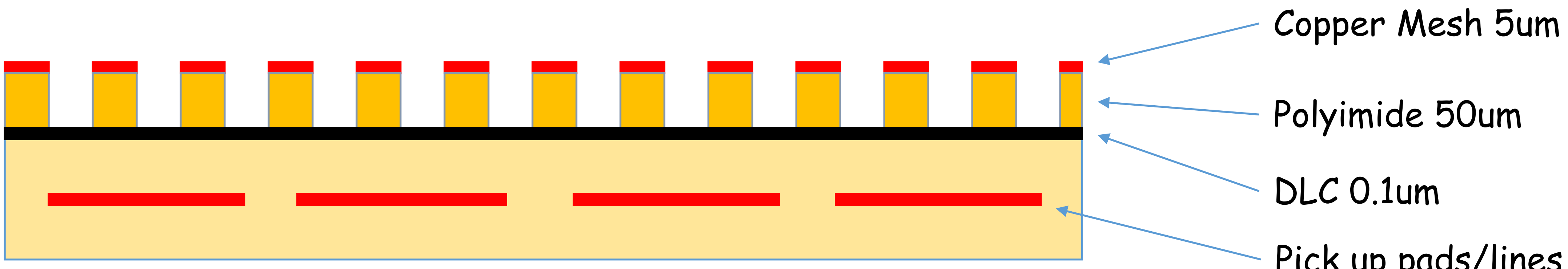




10cm x 10cm
µRwell detector
drill and fill
And SBU

Large µRwell detector
Like CMS GE21 module M4
120cm x 55cm

Classical μRwell



\+
1 gluing/1 patterning/1 etching
Probably the simplest MPGD
Single piece
Flexible

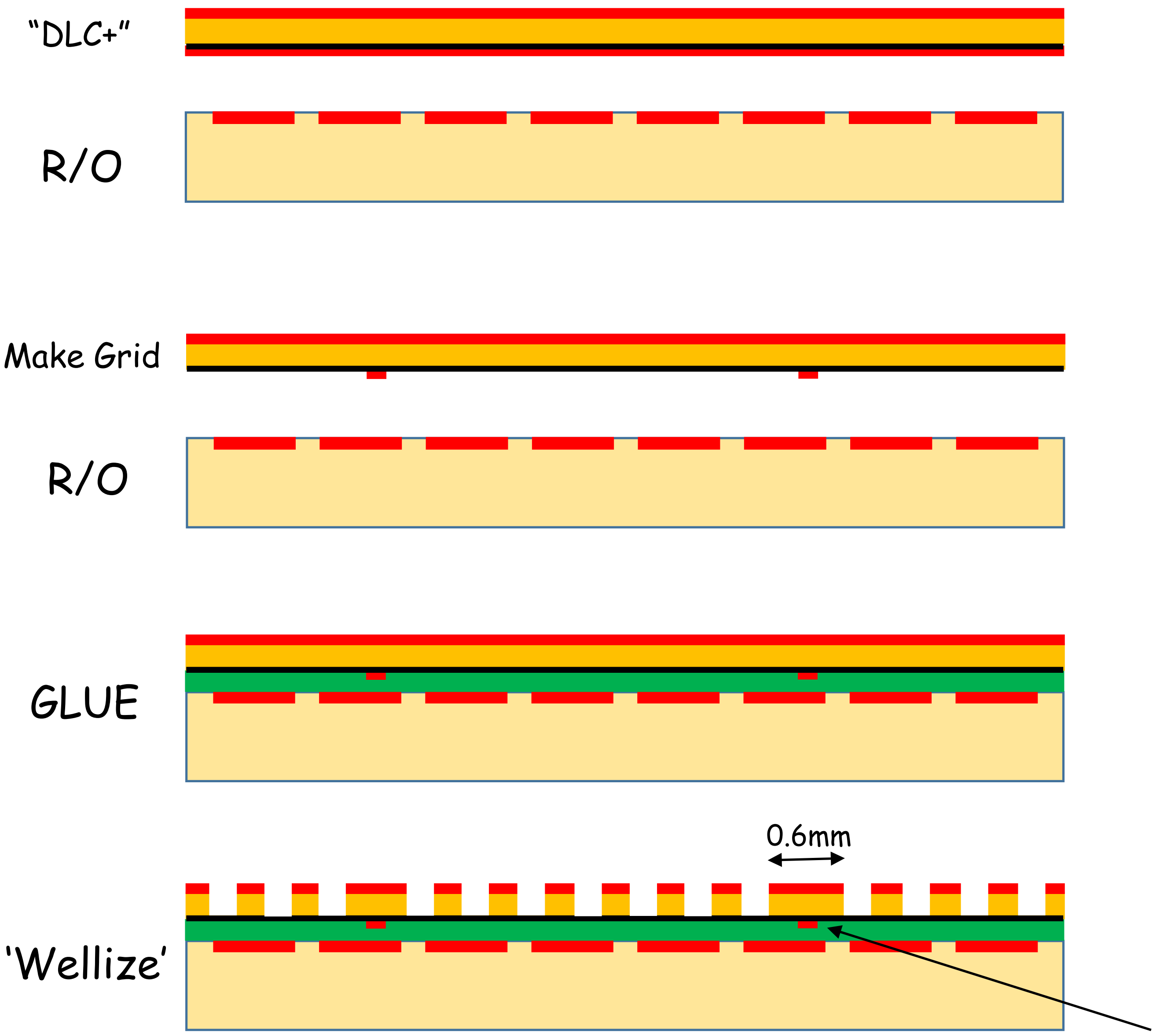
\-
Lateral current evacuation

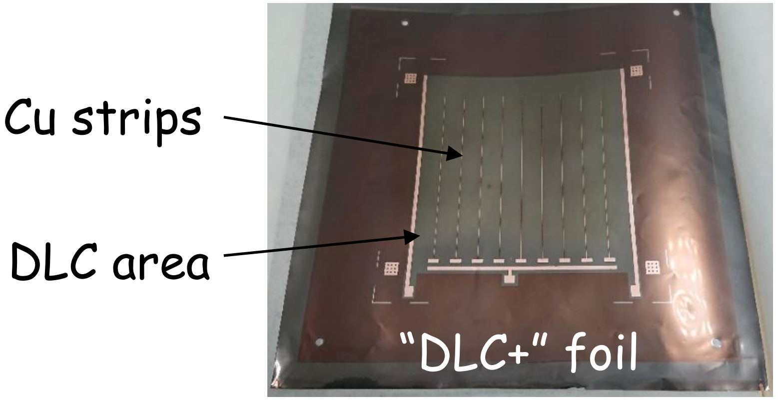
Delivered to : Stony Brook , Novosibirsk, Virginia ,China, Frascati
Sizes from 10cm x 10cm up to 1.2m x 0.5m

SG type:

Silver or Cu Grid

- Really simple construction
- Low cost
- Any resistive value can be proposed
- Adjustable evacuation line density VS rate
- Efficiency is design dependent
- No major resistive change during production
- Needs copper plated “DLC+”
- DOCA accuracy depends on mesh to line registration
- Subject to 0.5mm line to mesh miss-registration in 1m size
  - Mesh to line miss-registration critical above 100um
  - Needs an distortion scaling system to pattern the mesh





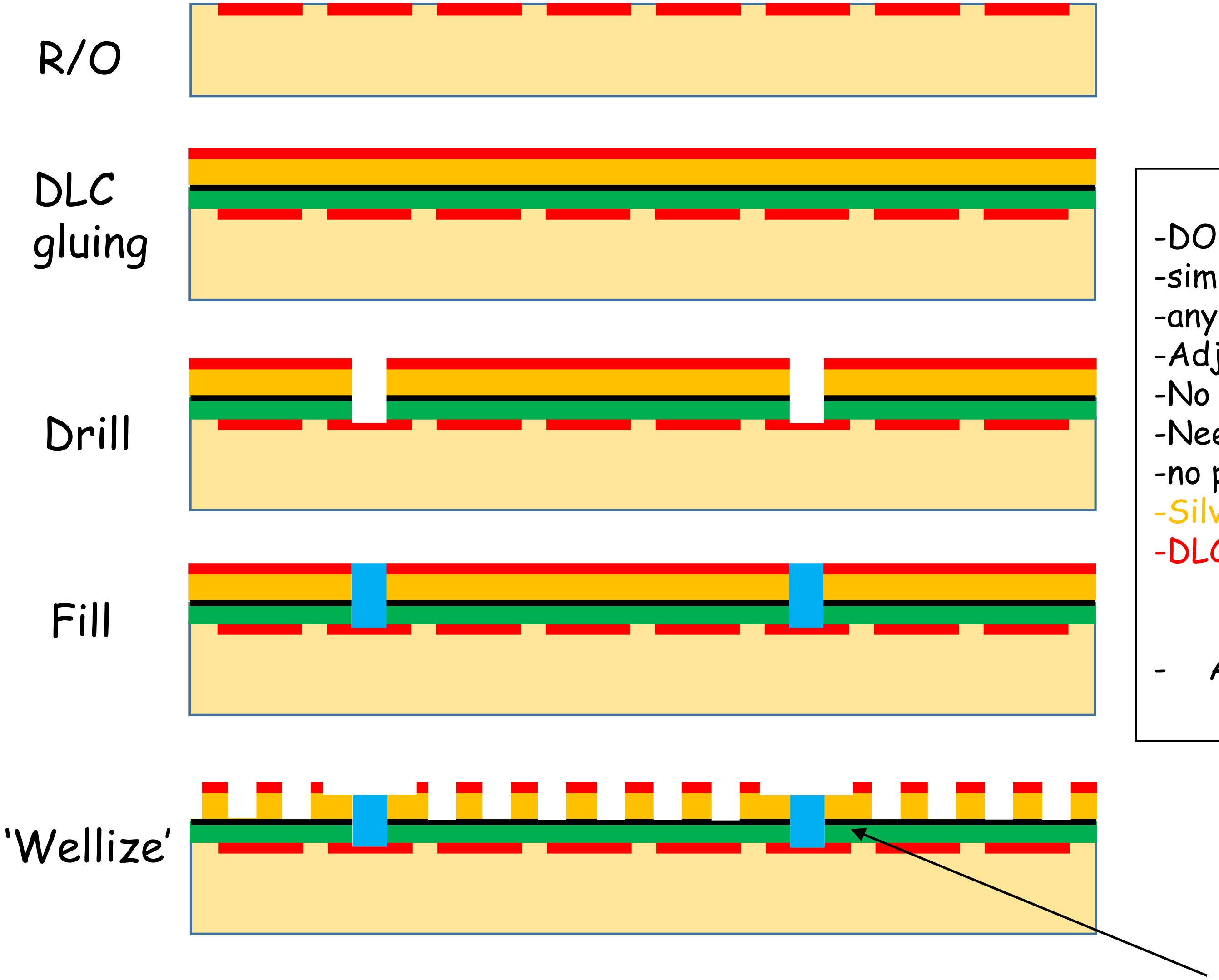
DOCA: 0.25mm for 80M

0.1mm Cu line , 12mm pitch

0.6mm blind zone → efficiency above 97%

DF Type

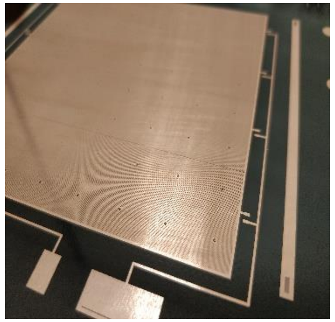
Drill and Fill

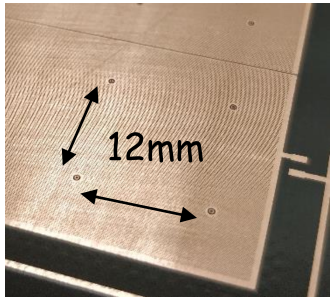


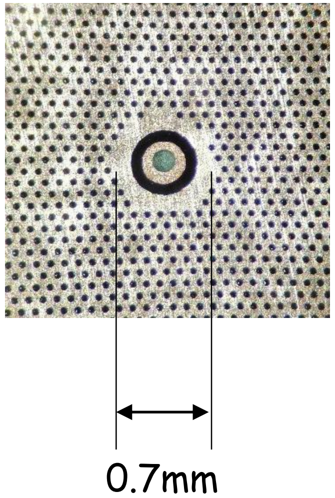
-DOCA under better control
-simple construction
-any resistive value
-Adjustable evacuation point density VS rate
-No major resistive change during production
-Needs simple DLC foils
-no problem for large size registration
-Silver filling is not STD in PCB world
-DLC to silver contact need to be improved

- A solution is in progress to address these 2 last points

DOCA : 0.25mm
0.2mm hole
0.7mm dead zone



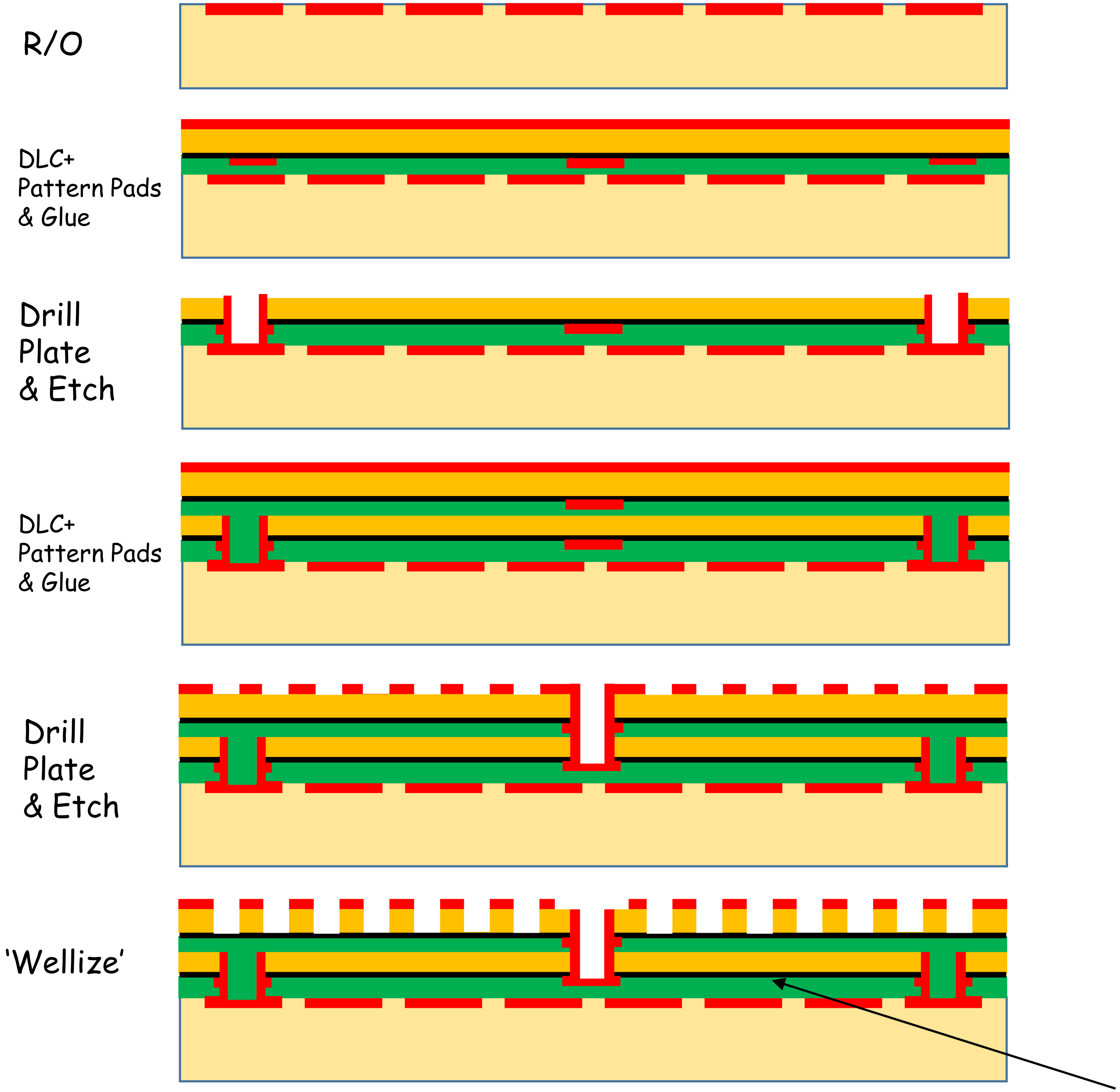




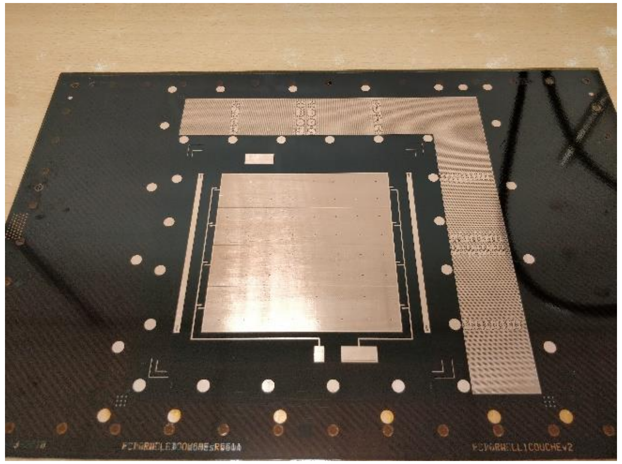
SBU type

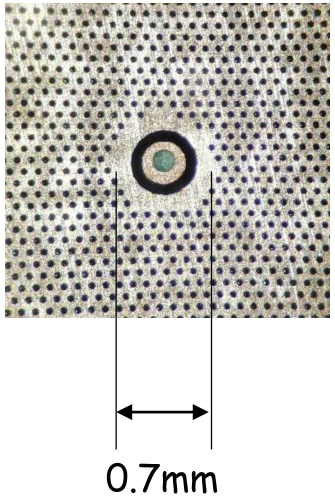
Sequential Build Up

- -Extra Large DOCA
- -Any resistive value can be used
- -Adjustable evacuation point density VS rate
- -No major resistive change during production
- -Needs copper plated DLC+
- -possible layers miss-registration up to 0.5mm in large size
  - -Miss-registration critical above 0.5mm
- -100% compatible with STD PCB processes



DOCA : 6mm





Summary on uRwell

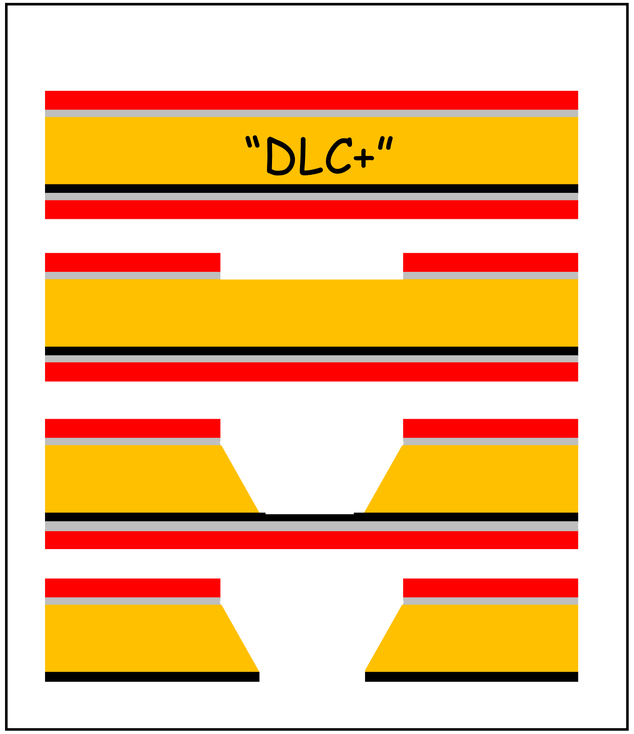
- We have now solutions for :
  - Large spreading
  - High rate
  - Small pads
  - Large size

- We need to improve the “DLC+” material to propose a solution 100% compatible with industry.

- We need also to work on the DLC resistive value prediction with “DLC+” materials

- DLC can be patterned

DLC Resistive GEM

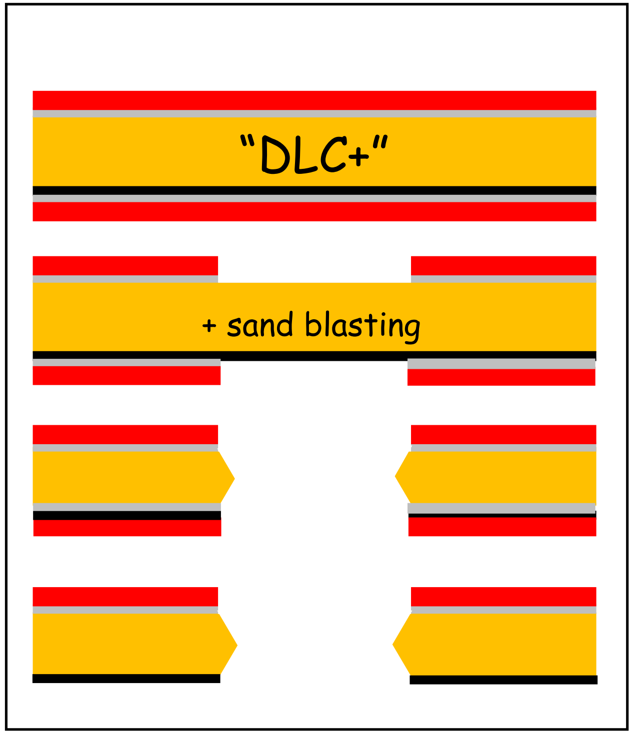


Cu/Cr pattern

Kapton etch

Cu/Cr etch

FTM process



Minimizing distortions with sectored GEM electrodes

A.P. Marques[a,b], F.M. Brunbauer[a,*], H. Müller[a], R. de Oliveira[a], E. Oliveri[a], D. Pfeiffer[a,c], L. Ropelewski[a], J. Samarati[a,c], F. Sauli[a], L. Scharenberg[a,d], L. Shang[e], M. van Stenis[a], S. Williams[a], Y. Zhou[f]

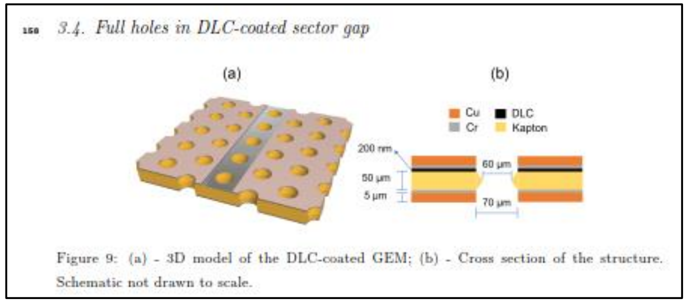
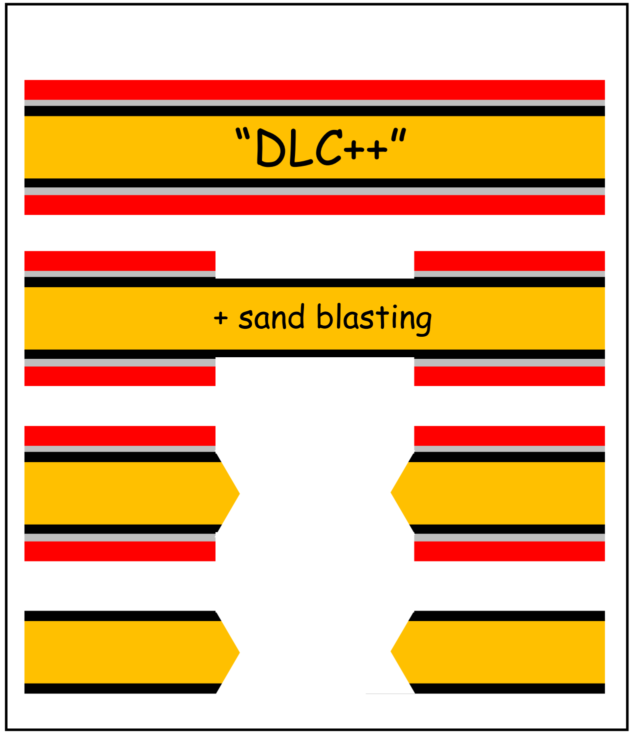
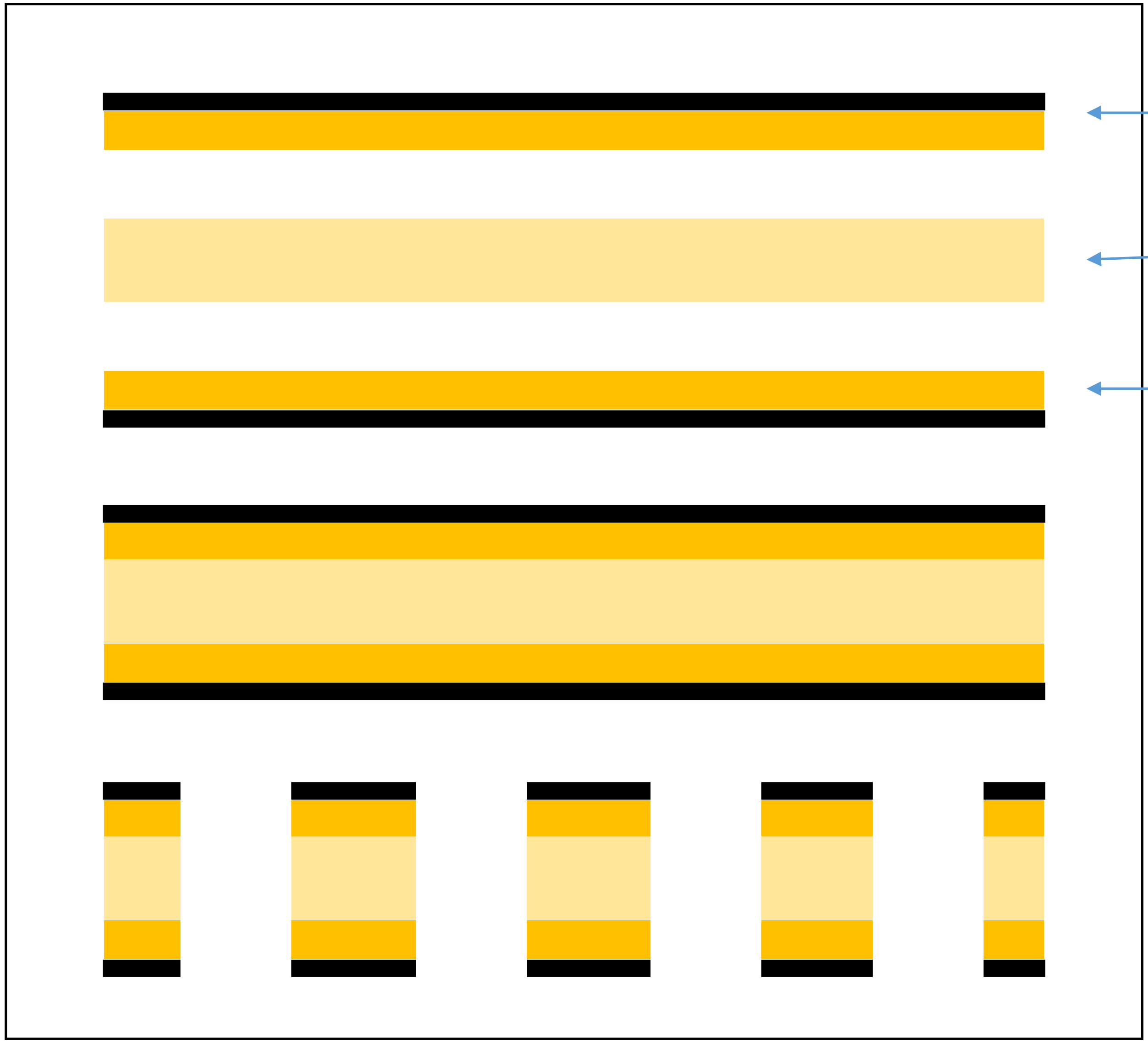

150 *3.4. Full holes in DLC-coated sector gap*

Figure 9: (a) - 3D model of the DLC-coated GEM; (b) - Cross section of the structure. Schematic not drawn to scale.



In progress
Waiting for good base material

Resistive THGEM



Kapton with DLC

PCB

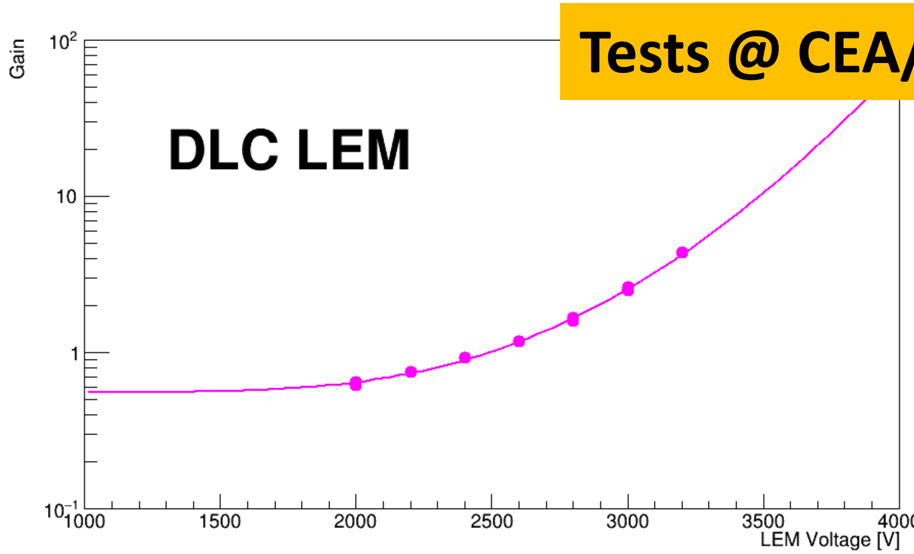
Kapton with DLC

Glue the 3 parts with prepreg

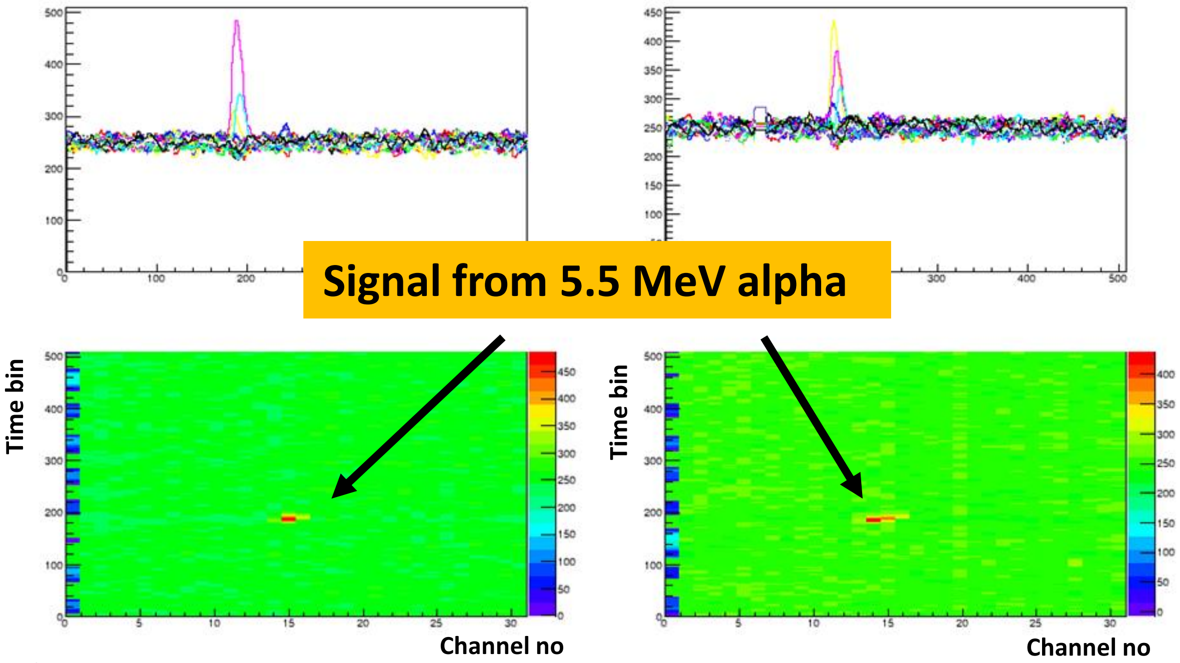
Drilling like a THGEM

Resistive LEM

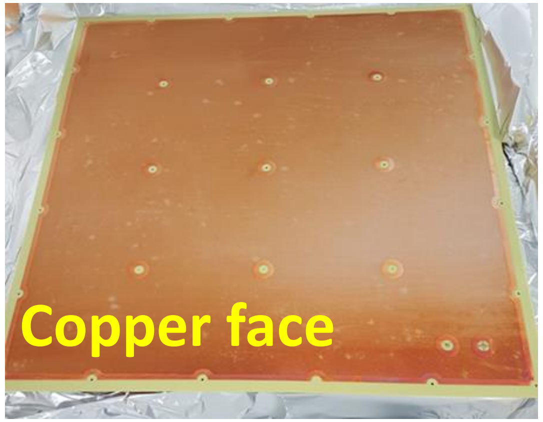
- Quenching of discharges with resistive 50×50 cm^2 LEM :
- Made at CERN EP-DT-EF :
  - - copper side facing readout anode
  - - DLC on 50 µm APICAL polyimide film (250 MΩ/□)
  - - same geometry as CFR-35 (ProtoDUNE-DP)
  - - no rims, no gold plating on copper face.
- Tests in progress at CEA/Irfu.
- R&D will continue in collaboration with CERN.



Tests @ CEA/Irfu

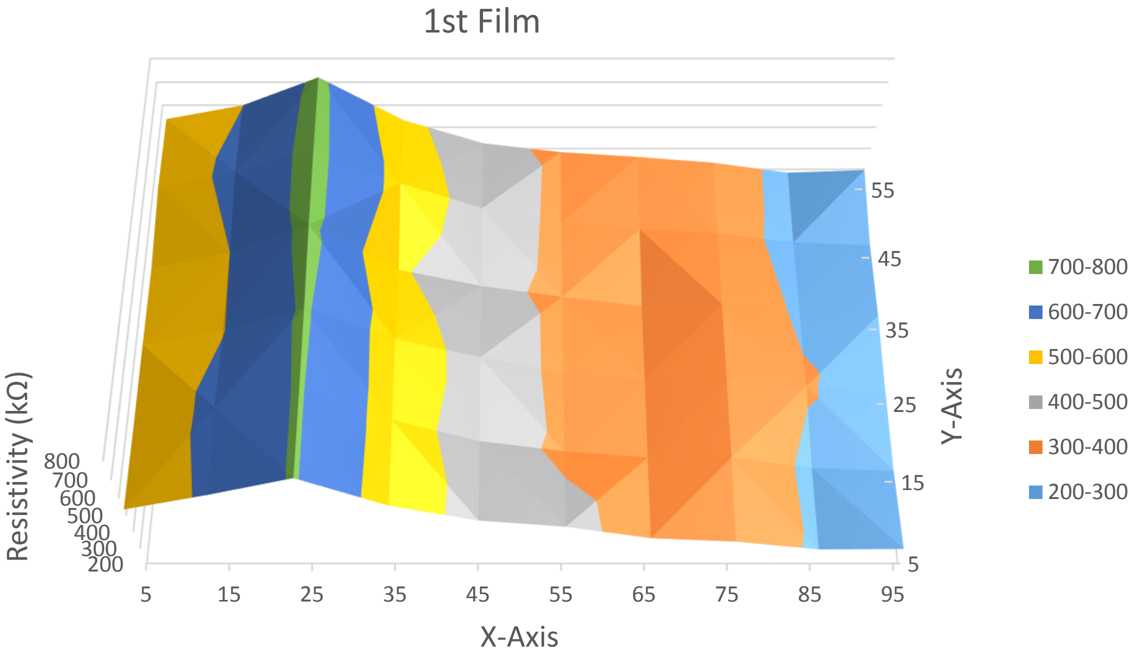


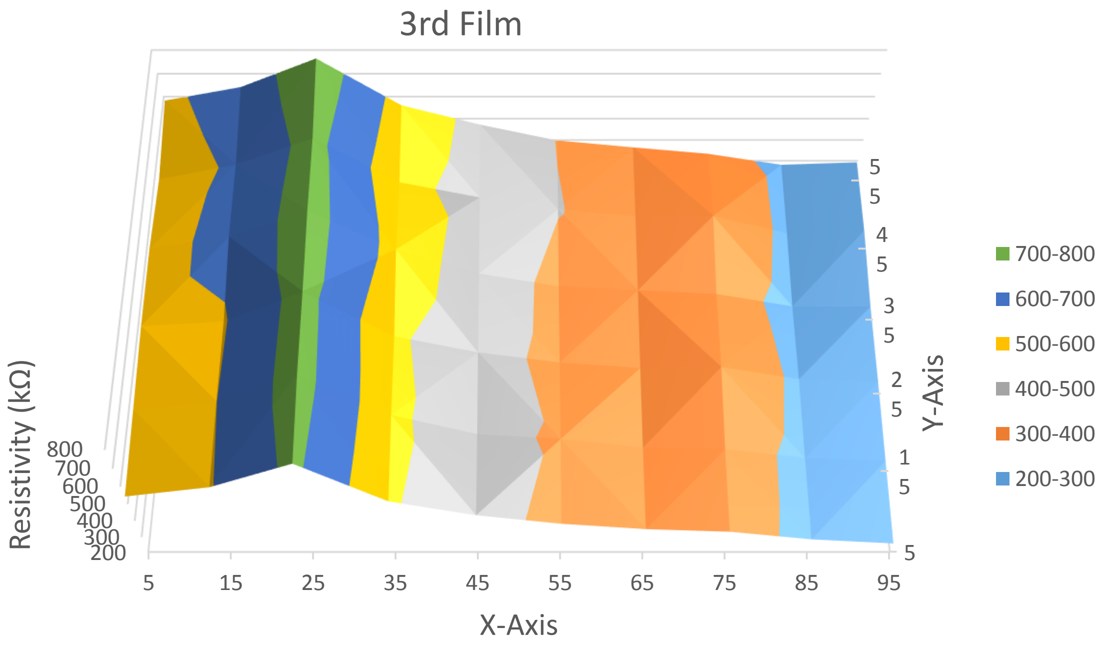
Signal from 5.5 MeV alpha



Problems with
-DLC
-DLC+

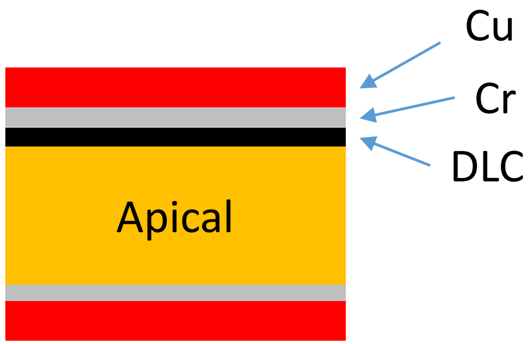
DLC uniformity

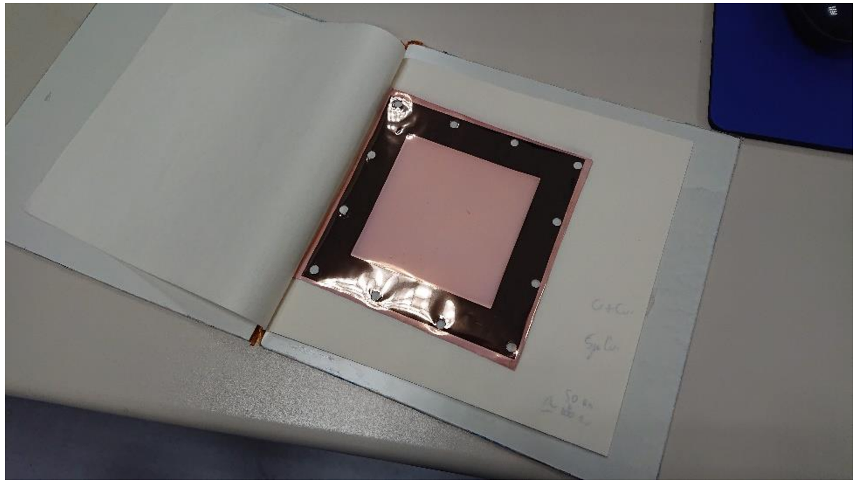


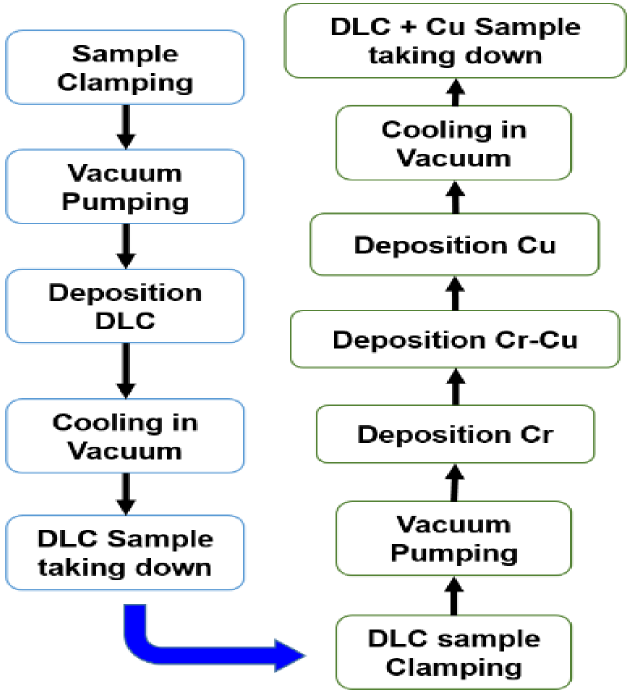


1m x 0.6m foils 500Kohms/square target

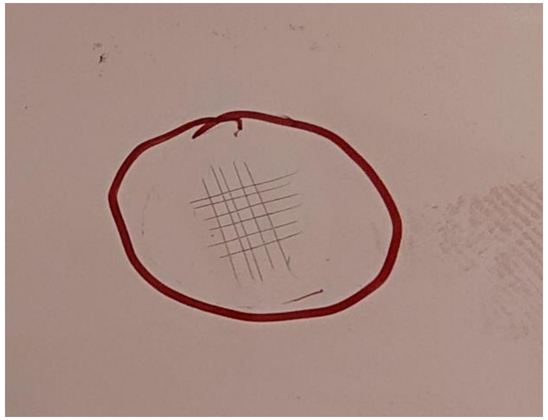
"DLC+" adhesion



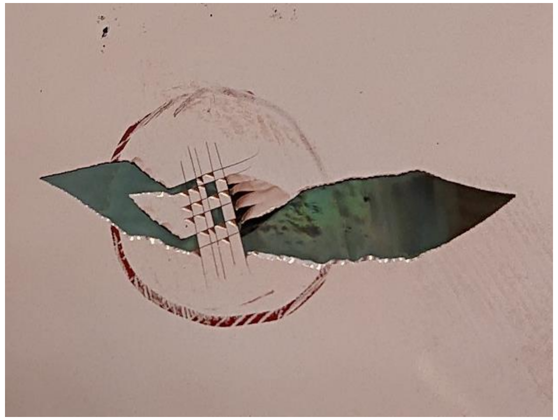




Sample Clamping
Vacuum Pumping
Deposition DLC
Cooling in Vacuum
DLC Sample taking down
DLC sample Clamping
Vacuum Pumping
Deposition Cr
Deposition Cr-Cu
Deposition Cu
Cooling in Vacuum
DLC + Cu Sample taking down



Scalpel cut



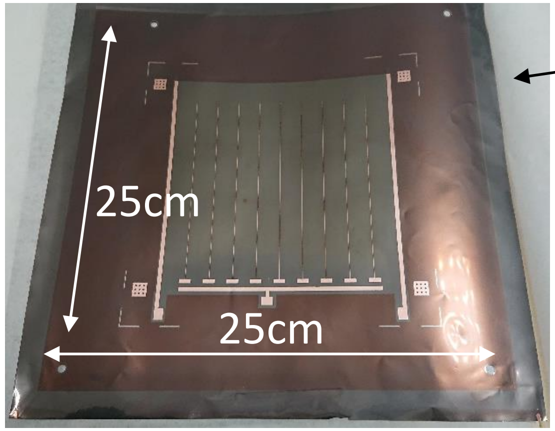
After tape peeling

Adhesion force estimation

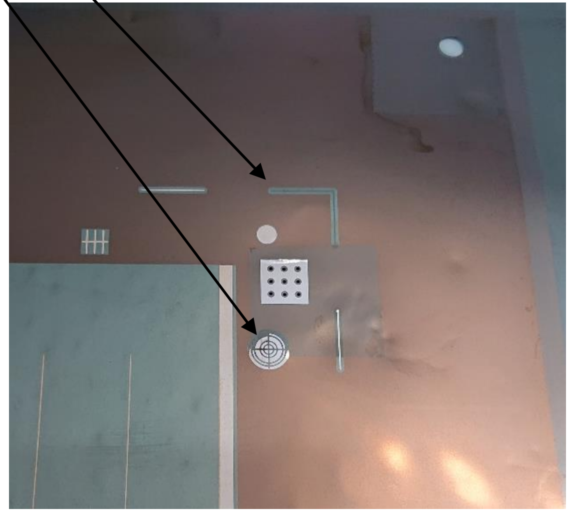
100%	Base material
50%	HEIFEI 300 deg deposition
40%	ESS
30%	HEIFEI center of the foil
10%	HEIFEI outer Part

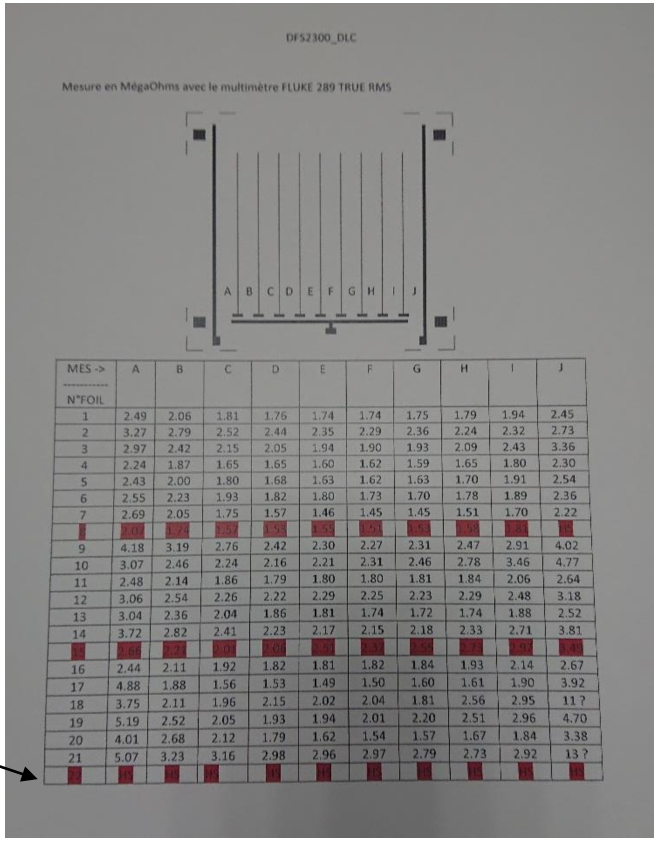
The DLC Value is always much lower after copper removal (HEIFEI but also ESS) by a factor of 4 to 10

"DLC+" : present adhesion is just at the acceptable level



20 foils produced → SG detectors
Resistor shape factor of 10
20 Mohms/sqr instead of 80 expected
Lower values at the center
Good repeatability
Signs of weak Cu/Cr to DLC interface
on 3 foils





DFS2300_DLC

Mesure en MégaOhms avec le multimètre FLUKE 289 TRUE RMS

MES -> ---------- N°FOIL	A	B	C	D	E	F	G	H	I	J
1	2.49	2.06	1.81	1.76	1.74	1.74	1.75	1.79	1.94	2.45
2	3.27	2.79	2.52	2.44	2.35	2.29	2.36	2.24	2.32	2.73
3	2.97	2.42	2.15	2.05	1.94	1.90	1.93	2.09	2.43	3.36
4	2.24	1.87	1.65	1.65	1.60	1.62	1.59	1.65	1.80	2.30
5	2.43	2.00	1.80	1.68	1.63	1.62	1.63	1.70	1.91	2.54
6	2.55	2.23	1.93	1.82	1.80	1.73	1.70	1.78	1.89	2.36
7	2.69	2.05	1.75	1.57	1.46	1.45	1.45	1.51	1.70	2.22
8	2.07	1.74	1.57	1.53	1.55	1.51	1.53	1.58	1.81	HS
9	4.18	3.19	2.76	2.42	2.30	2.27	2.31	2.47	2.91	4.02
10	3.07	2.46	2.24	2.16	2.21	2.31	2.46	2.78	3.46	4.77
11	2.48	2.14	1.86	1.79	1.80	1.80	1.81	1.84	2.06	2.64
12	3.06	2.54	2.26	2.22	2.29	2.25	2.23	2.29	2.48	3.18
13	3.04	2.36	2.04	1.86	1.81	1.74	1.72	1.74	1.88	2.52
14	3.72	2.82	2.41	2.23	2.17	2.15	2.18	2.33	2.71	3.81
15	2.66	2.21	2.01	2.06	2.51	2.37	2.55	2.73	2.97	3.49
16	2.44	2.11	1.92	1.82	1.81	1.82	1.84	1.93	2.14	2.67
17	4.88	1.88	1.56	1.53	1.49	1.50	1.60	1.61	1.90	3.92
18	3.75	2.11	1.96	2.15	2.02	2.04	1.81	2.56	2.95	11 ?
19	5.19	2.52	2.05	1.93	1.94	2.01	2.20	2.51	2.96	4.70
20	4.01	2.68	2.12	1.79	1.62	1.54	1.57	1.67	1.84	3.38
21	5.07	3.23	3.16	2.98	2.96	2.97	2.79	2.73	2.92	13 ?
22	HS	HS	HS	HS	HS	HS	HS	HS	HS	HS

conclusion

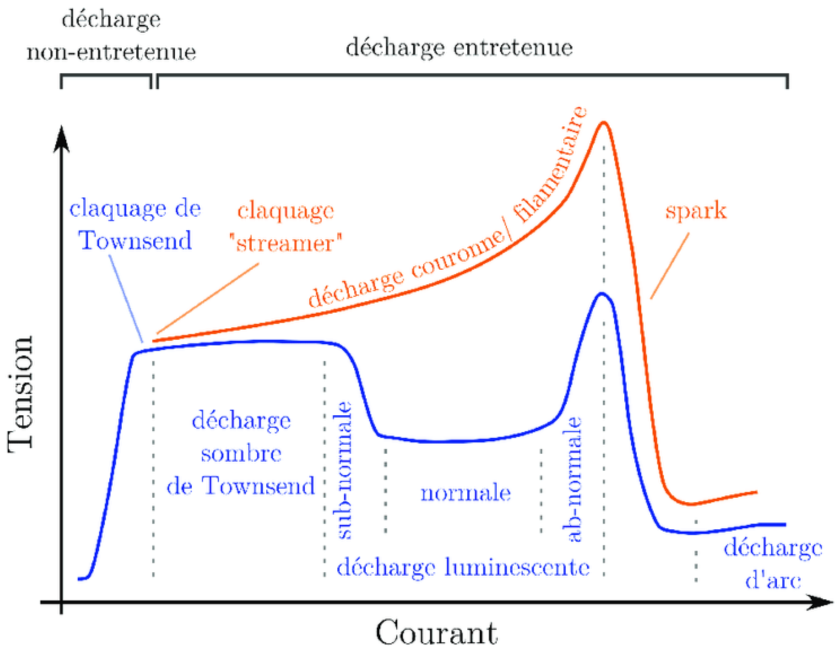
- We need to Improve the DLC+ and DLC++ materials
    - But robust solutions with simple DLC already exist

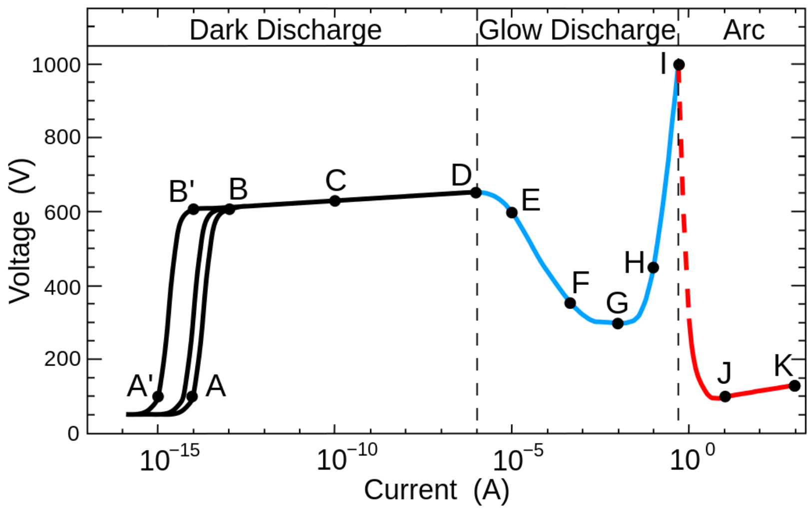
- We need to work on DLC uniformity
    - But the present uniformity is ok for a lot of applications

- DOCA study should be continued
    - Find the parameter to adjust material evaporation (design and materials)

Thank you

Questions?





Voltage versus current characteristics for neon gas at 1 Torr pressure between flat electrodes spaced 50 cm.

A-D dark discharge

A-B: non-self-sustaining discharge and collection of spontaneously-generated ions.

B-D: the Townsend region, where the cascade multiplication of carriers takes place.

D-I glow discharge

D-E: transition to a glow discharge, breakdown of the gas.

E-G: transition to a normal glow; in the regions around G, voltage is nearly constant for varying current.

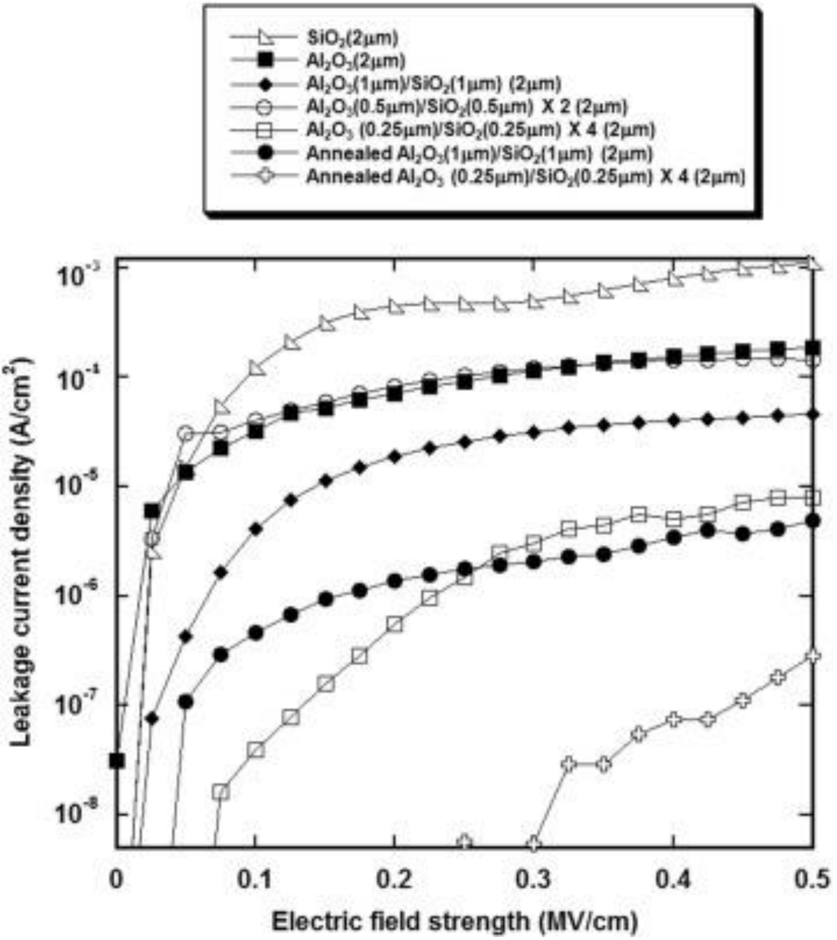
G-I: represents abnormal glow, as current density rises

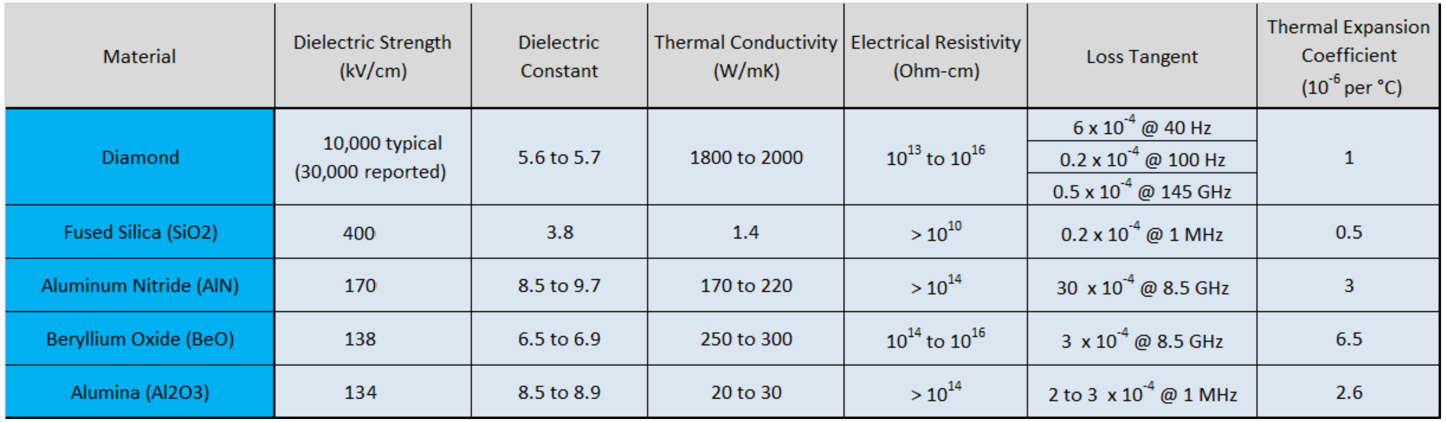
I-K arc discharge

Thin Solid Films
Volume 595, Part A, 30
November 2015, Pages
171-175

Electrical insulation and breakdown properties of SiO_2 and Al_2O_3 thin multilayer films deposited on stainless steel by physical vapor deposition

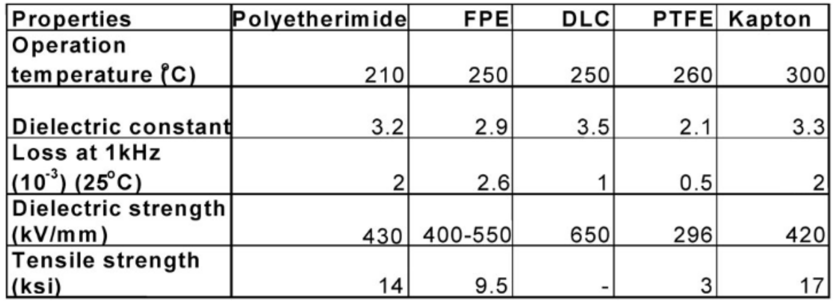
Author links open overlay panelJosuMartinez-Perdiguero[ab]LuciaMendizabal[b]Maria C.Morant-Miñana[ac]IreneCastro-Hurtado[ac]AritzJuarros[ab]RocíoOrtiz[ad]AinaraRodriguez[ac]





Material	Dielectric Strength (kV/cm)	Dielectric Constant	Thermal Conductivity (W/mK)	Electrical Resistivity (Ohm-cm)	Loss Tangent	Thermal Expansion Coefficient (10^{-6} per °C)
Diamond	10,000 typical (30,000 reported)	5.6 to 5.7	1800 to 2000	10^{13} to 10^{16}	6 x 10^{-4} @ 40 Hz 0.2 x 10^{-4} @ 100 Hz 0.5 x 10^{-4} @ 145 GHz	1
Fused Silica (SiO2)	400	3.8	1.4	> 10^{10}	0.2 x 10^{-4} @ 1 MHz	0.5
Aluminum Nitride (AlN)	170	8.5 to 9.7	170 to 220	> 10^{14}	30 x 10^{-4} @ 8.5 GHz	3
Beryllium Oxide (BeO)	138	6.5 to 6.9	250 to 300	10^{14} to 10^{16}	3 x 10^{-4} @ 8.5 GHz	6.5
Alumina (Al2O3)	134	8.5 to 8.9	20 to 30	> 10^{14}	2 to 3 x 10^{-4} @ 1 MHz	2.6

figure 5. Dielectric, resistivity and thermal properties of diamond and other electrically insulating material. Source: NIST, Manufacturers and R&D Literature



Properties	Polyetherimide	FPE	DLC	PTFE	Kapton
Operation temperature (°C)	210	250	250	260	300
Dielectric constant	3.2	2.9	3.5	2.1	3.3
Loss at 1kHz (10^{-3}) (25°C)	2	2.6	1	0.5	2
Dielectric strength (kV/mm)	430	400-550	650	296	420
Tensile strength (ksi)	14	9.5	-	3	17

figure 6. Capacitors dielectric materials comparison.
Source: IEEJ Dielectric Materials for Capacitors