Diamond Like Carbon for the Fast Timing MPGD

Piet Verwilligen

on behalf of FTM-next collaboration

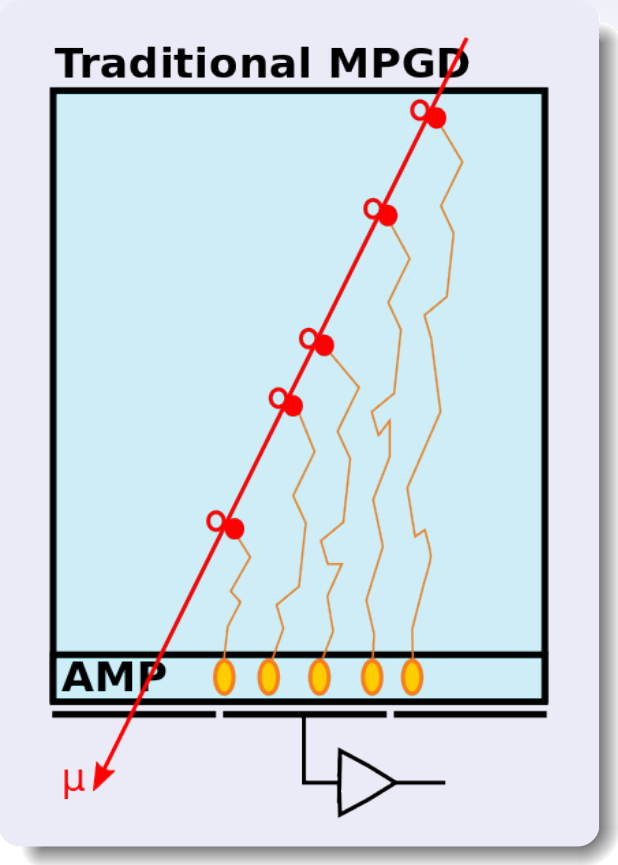
INFN sez. Bari, Lecce, Pavia (IT)
CERN (CH)
UGent (BE)

MPGD 2019 LA ROCHELLE

MPGD19 La Rochelle
May 7th 2019

INFN Istituto Nazionale di Fisica Nucleare

Fast Timing MPGD Principle



σ_t driven by distance fluct's

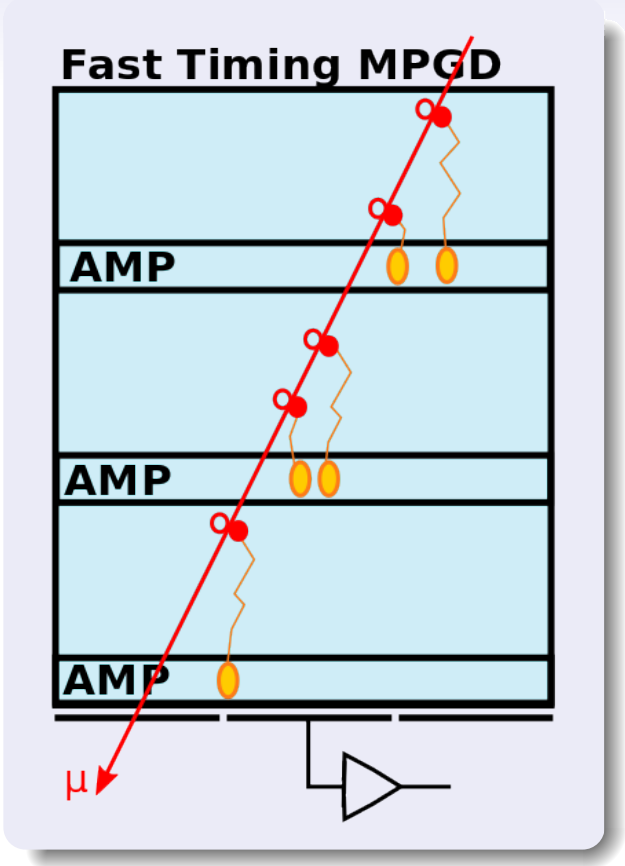
$$\sigma_t \propto 1/(\lambda v_{\text{drift}})$$

$\lambda = \#$ primary cls / mm

electron-ion pairs created close to amplification structure result in fast signals

Fast Timing MPGD: split drift volume in N layers, each with own amplification structure

$$\sigma_t \propto 1/(\lambda v_{\text{drift}} N)$$



- **choice of resistivity is trade-off** between high transparency & low signal spread (**high R**) and high rate capability (**low R**)
- **time resolution improves with N = number of layers**

Diamond Like Carbon (DLC)

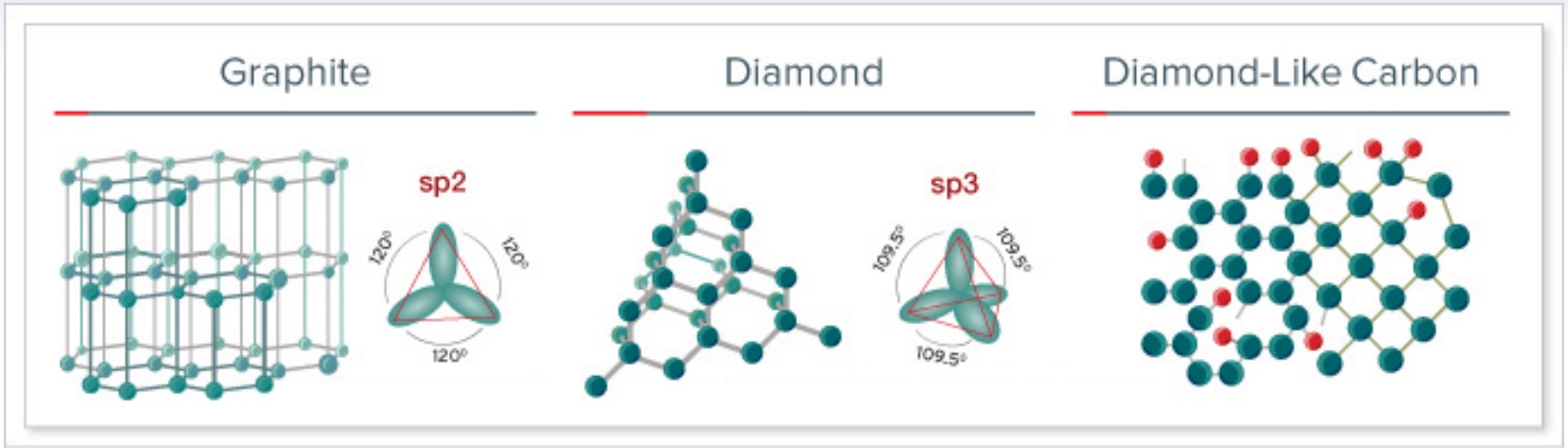


image credit www.dynasil.com

- Diamond-like carbon (DLC) is **hard, amorphous carbon film** with a significant fraction of **sp3**-hybridized carbon atoms and lower sp2-hybrid, H and dopants (N,B,...)
- **Properties can be tuned** through sp^3 fraction, size and concentration of sp^2 sites and hydrogen content
- Wide range of **applications**: reduce abrasive wear & friction, engines, Hard Disks, medical app, beer, ...

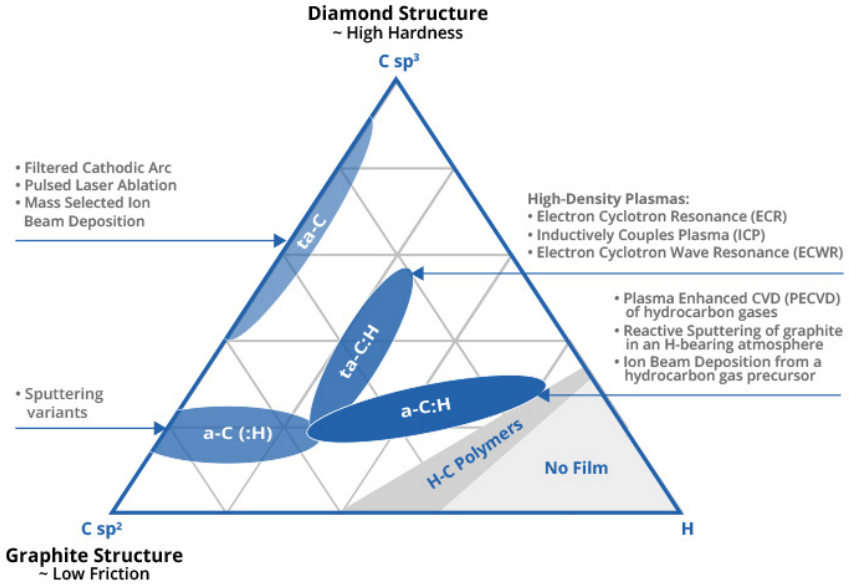
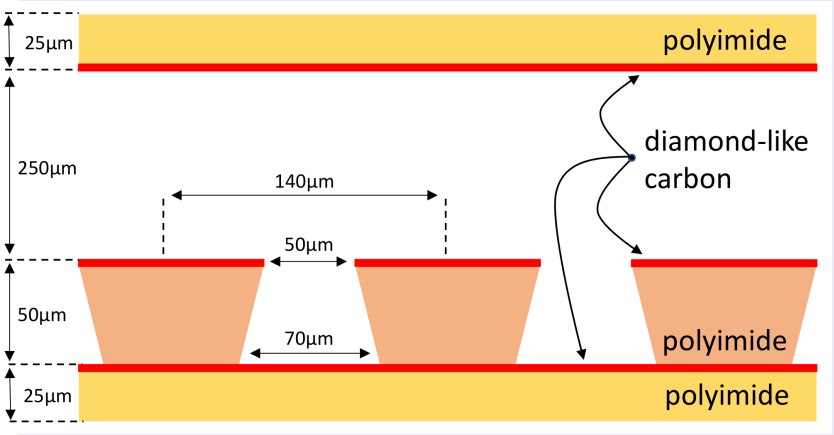


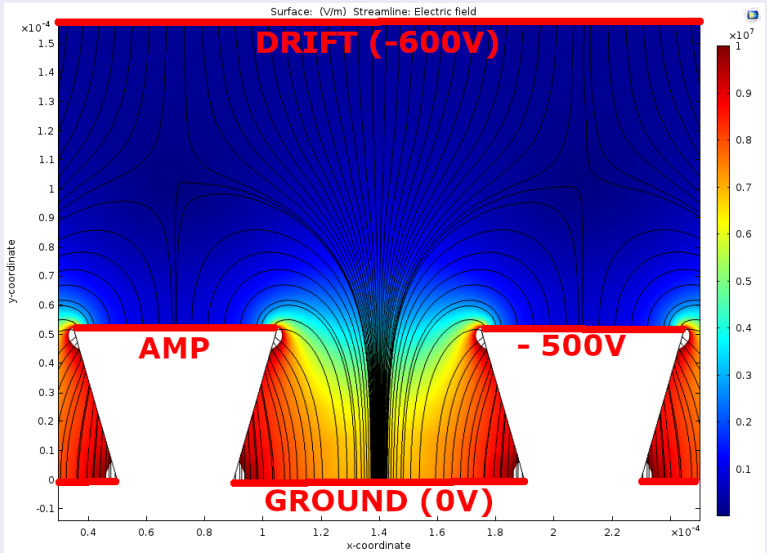
image credit: www.hefusa.net

See also talk Lunlin Shang - Thu 9/05

Fast Timing MPGD

polyimide prototype

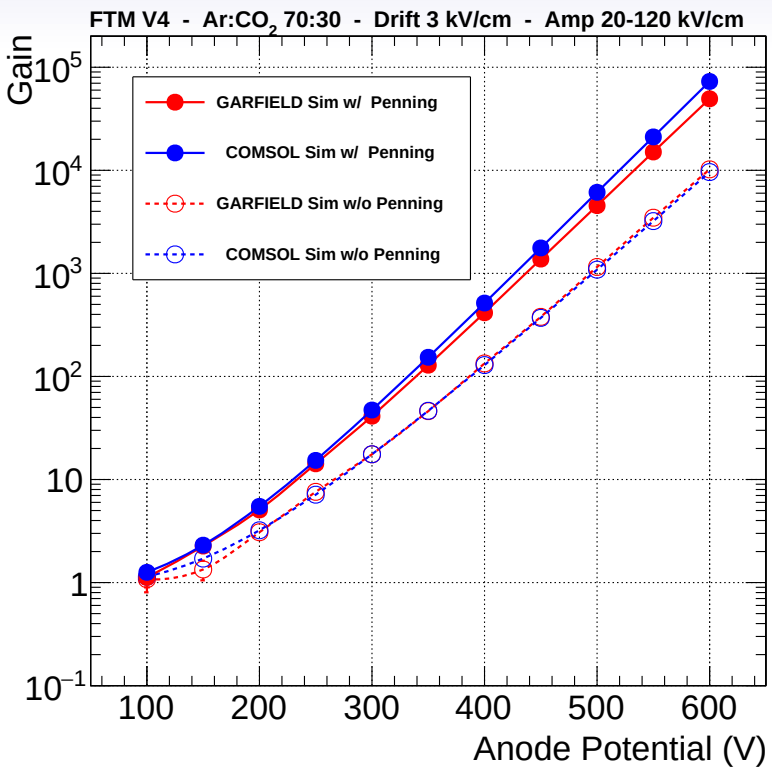


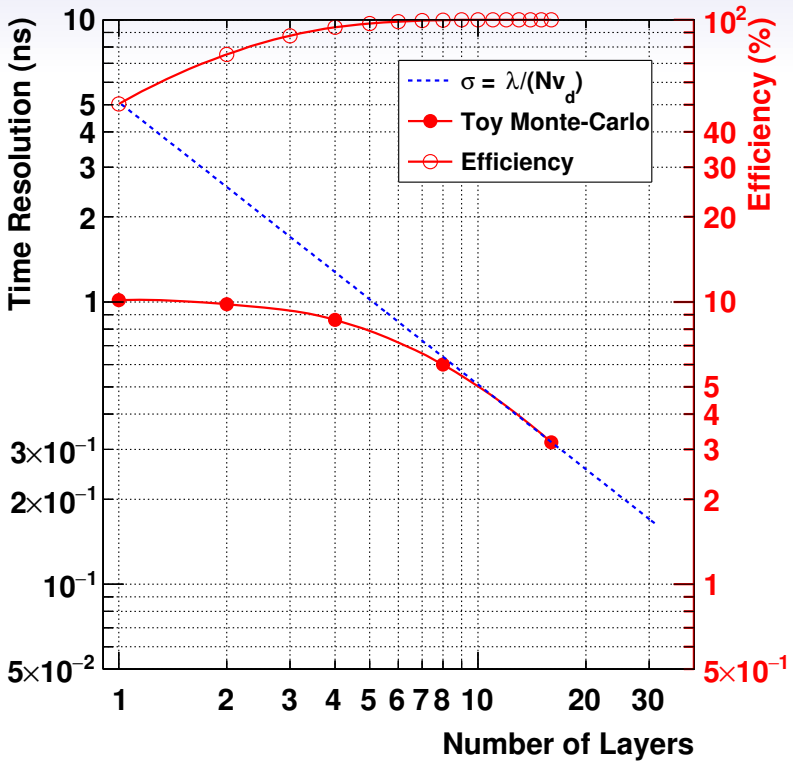


Single layer specifications:

- Drift layer: 250 μm drift layer (Dupont Coverlay spacers) [575-625 V]
- Gain layer: 50 μm kapton (70 μm hole, 140 μm pitch) [500–550 V]
- Resistive coating: 10–100 nm (Diamond Like Carbon) [electrodes]

Fast Timing MPGD



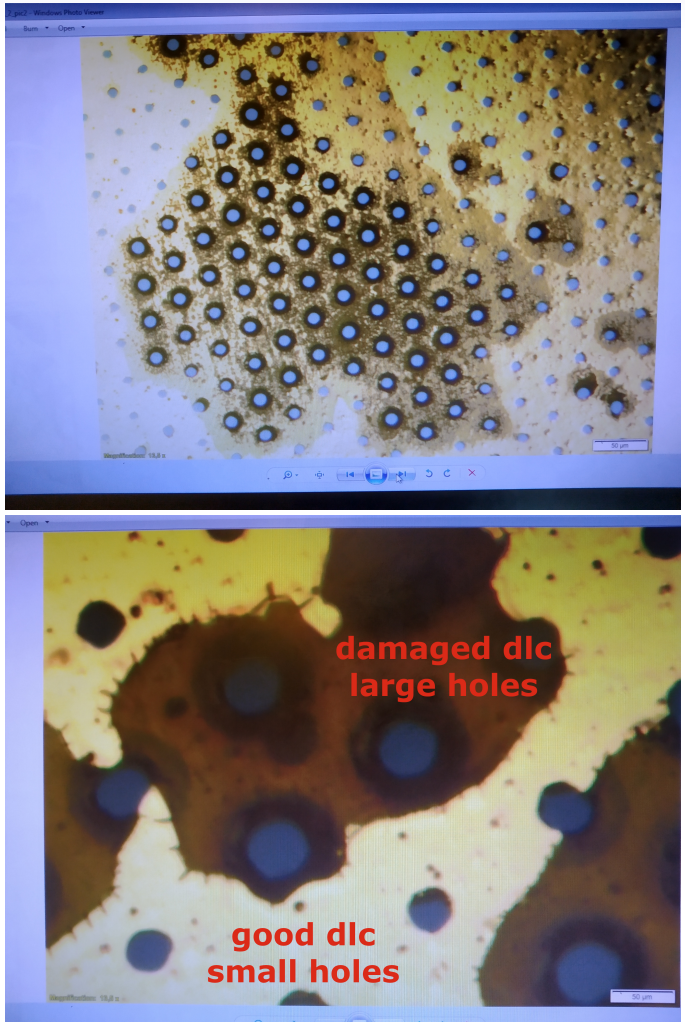


Detector simulations:

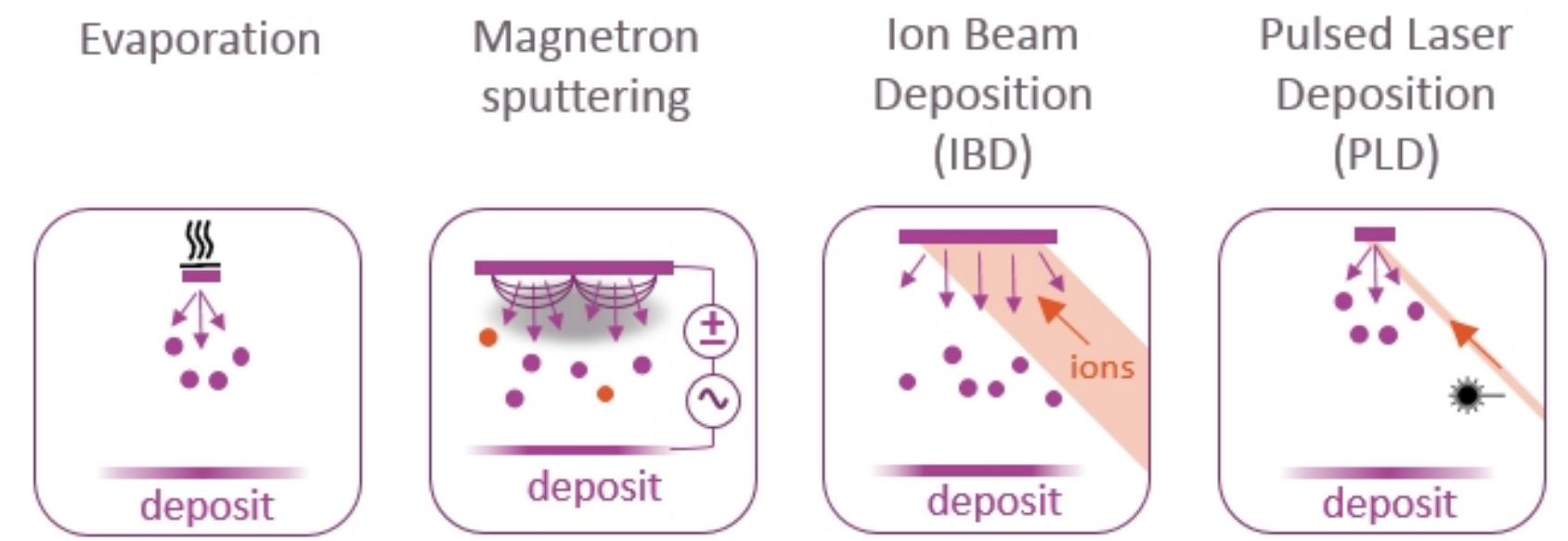
- Garfield & COMSOL sims validated (μRWELL data); reach $G \sim 5000$ at 500 V
- Toy Monte-Carlo $\Rightarrow$ ionisation eff & timing for 250 μm gaps (Ar:CO_2 70:30)
- SPICE simulations for signal transparency of different layers ongoing

Problems with etching of DLC coated PI

- **Production μRWELL:**
  - DLC coated PI film glued on PCB
  - good protection DLC during etching
- **Production FTM:**
  - DLC coated PI film without glueing
  - Rui uses thin film for protection DLC
  - not good enough . . . DLC delaminates
- **New FCCL: Cu-DLC-PI-Cu:**
  - produced by Yi Zhou at USTC
  - same prob: DLC delaminates
  - holes with large diameter = low gain
- **Problem with adhesion DLC to Polyimide**
- **Prompted Collaboration to investigate DLC**
  - INFN BA: Ion Beam Deposition
  - INFN LE: Pulsed Laser Deposition & Char



Physical Vapor Deposition (PVD)



- **Main difference: ion energy**
  - evaporation: $\mathcal{O}(0.1\,\mathrm{eV})$ sputter: $\mathcal{O}(0.1\text{–}10\,\mathrm{eV})$ ion beam $\mathcal{O}(10\text{–}100\,\mathrm{eV})$
- **advantages Magnetron Sputtering:**
  - fast process; large area; adopted by industry
- **advantages Ion Beam Sputtering:**
  - good quality film & good adhesion; can deposit many materials on many substrates (also non-conducting)
- **advantages Pulsed Laser Deposition:**
  - λ and J control sp_3/sp_2-ratio, many independent variables; precise control

Ion-beam sputtering Setup

- Room Temperature (23°C)
- Vacuum 10^{-5} mbar
- Pre-treatment with $O\bullet$ / $Ar\bullet$ radicals
- Ion Beam Source (1 keV, 100 mA)
- Assistant Source (100 eV, 1 A)
- Graphite Target: ∅10 cm
- Substrate: $6 \times 6\,\text{cm}^2$
- Quartz balance → film thickness
- Deposition speed ∼ 100 nm / hour

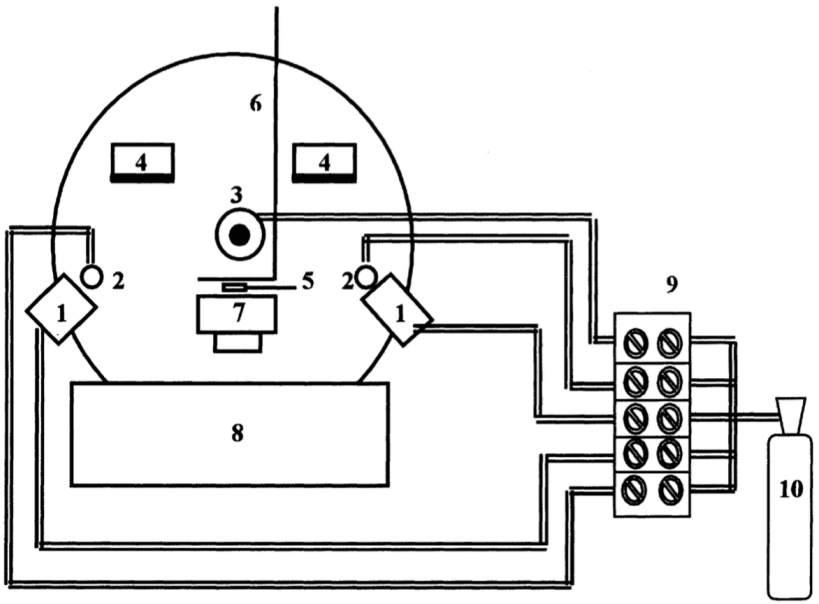
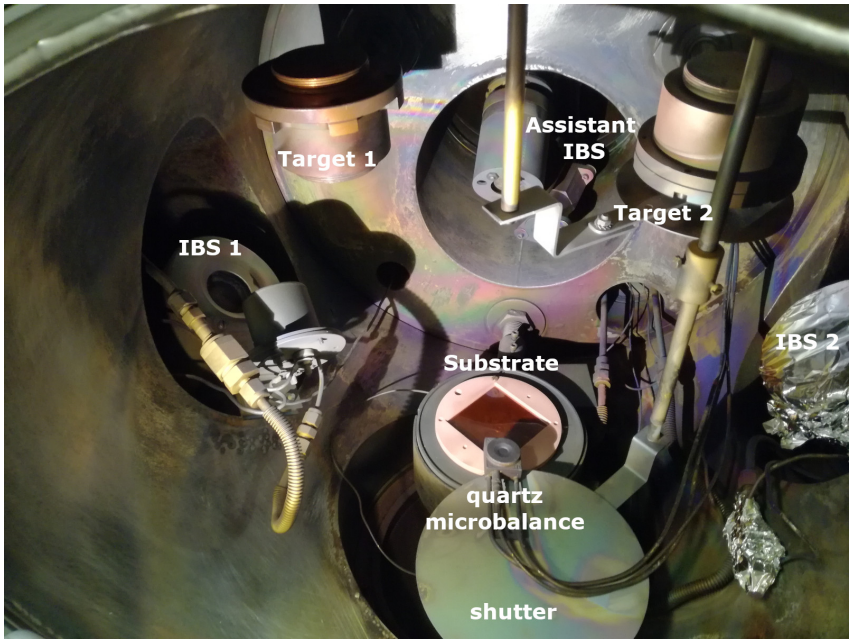


FIGURE 1 Schematic representation of the dual ion-beam sputtering deposition system used: (1) sputtering ion-beam sources, (2) plasma bridge neutralizers, (3) assistance ion-beam source, (4) targets, (5) quartz microbalance, (6) shutter, (7) substrate holder, (8) turbomolecular pump, (9) flow control unit, (10) argon supply

- First samples in Dec 2018;
- Followed with a few attempts with N_2 doping and many with H_2 doping 2019

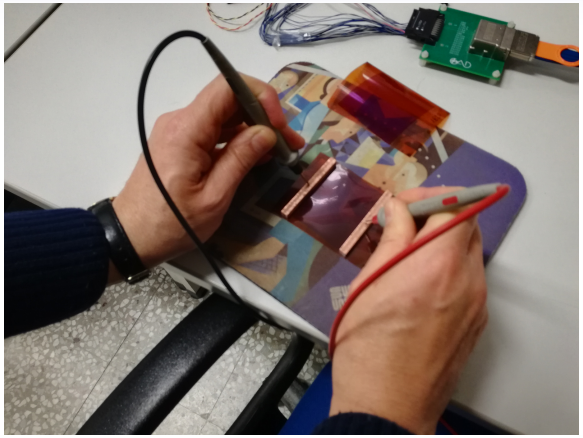
Ion-beam sputtering Setup

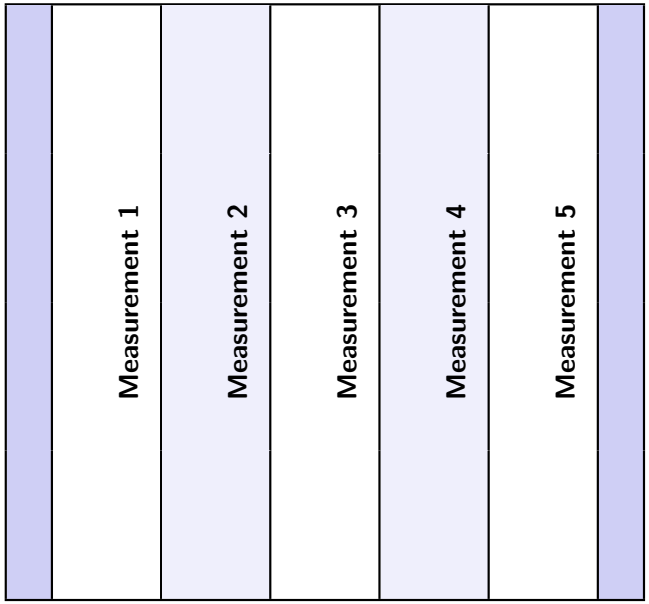
- Room Temperature (23°C)
- Vacuum 10^{-5} mbar
- Pre-treatment with $O\bullet$ / $Ar\bullet$ radicals
- Ion Beam Source (1 keV, 100 mA)
- Assistant Source (100 eV, 1 A)
- Graphite Target: ∅10 cm
- Substrate: $6 \times 6\,\text{cm}^2$
- Quartz balance → film thickness
- Deposition speed ∼ 100 nm / hour



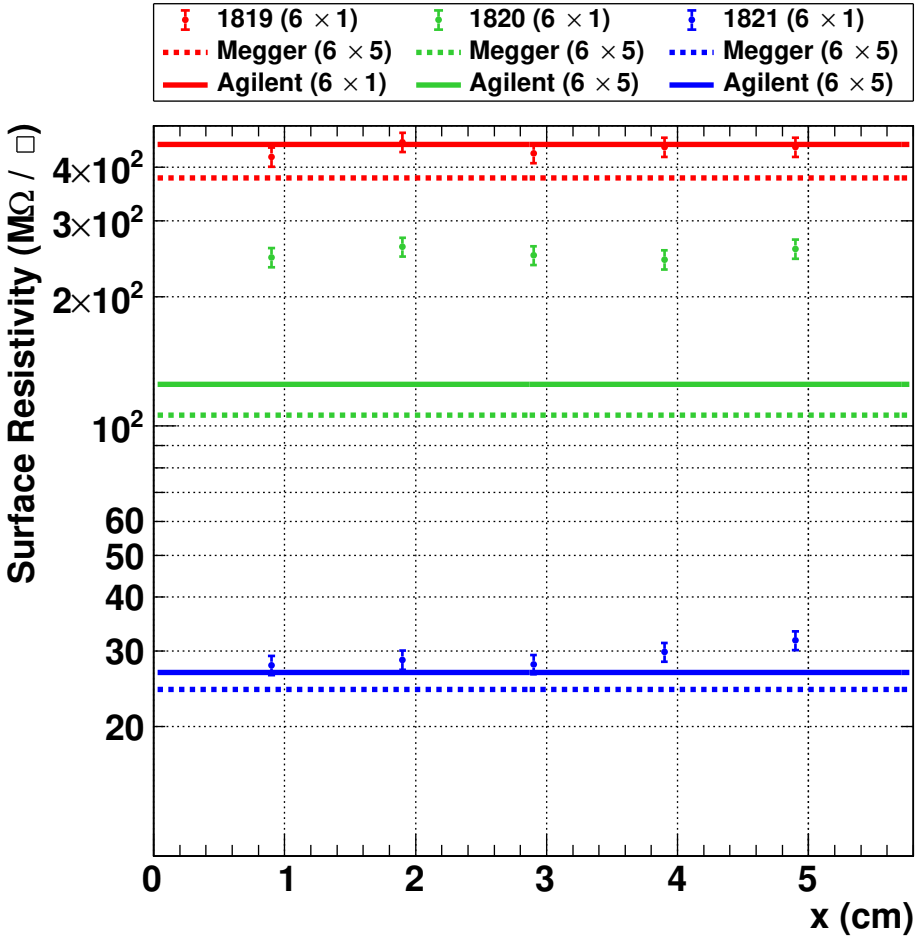
- First samples in Dec 2018;
- Followed with a few attempts with N_2 doping and many with H_2 doping 2019

Resistivity Measurements

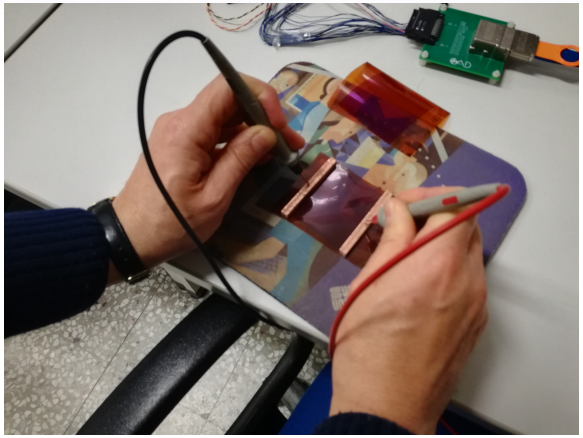




Uniformity (3–5%)

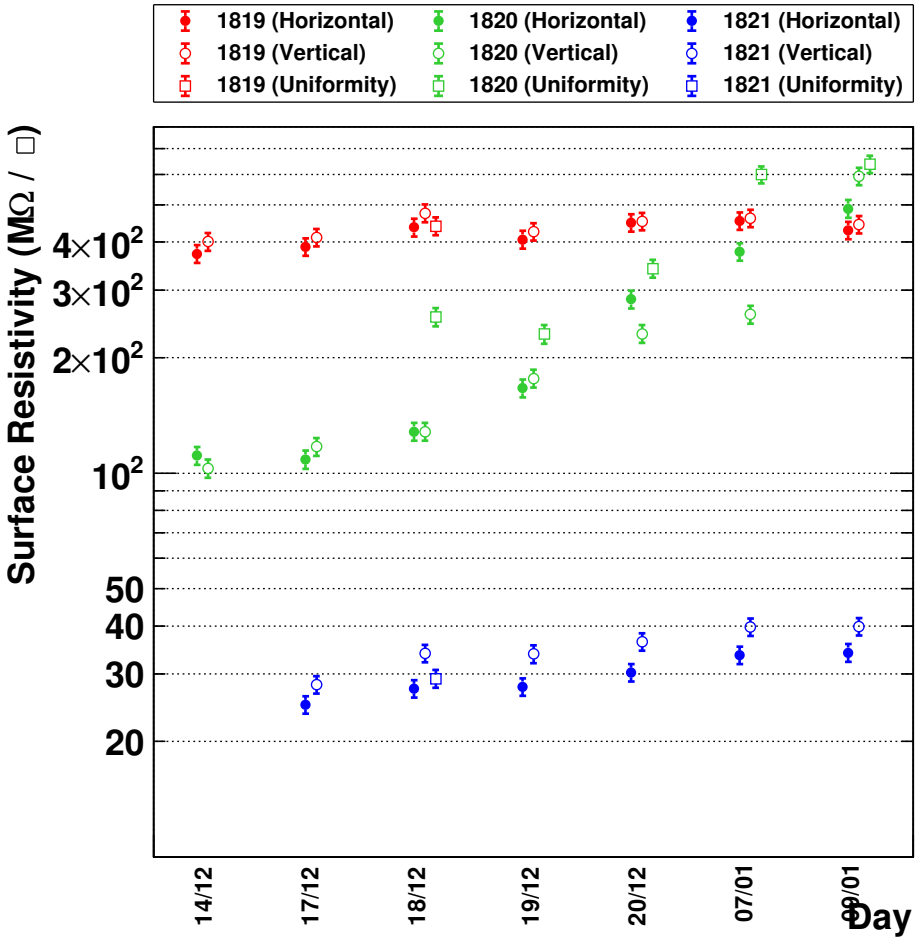


Resistivity Measurements

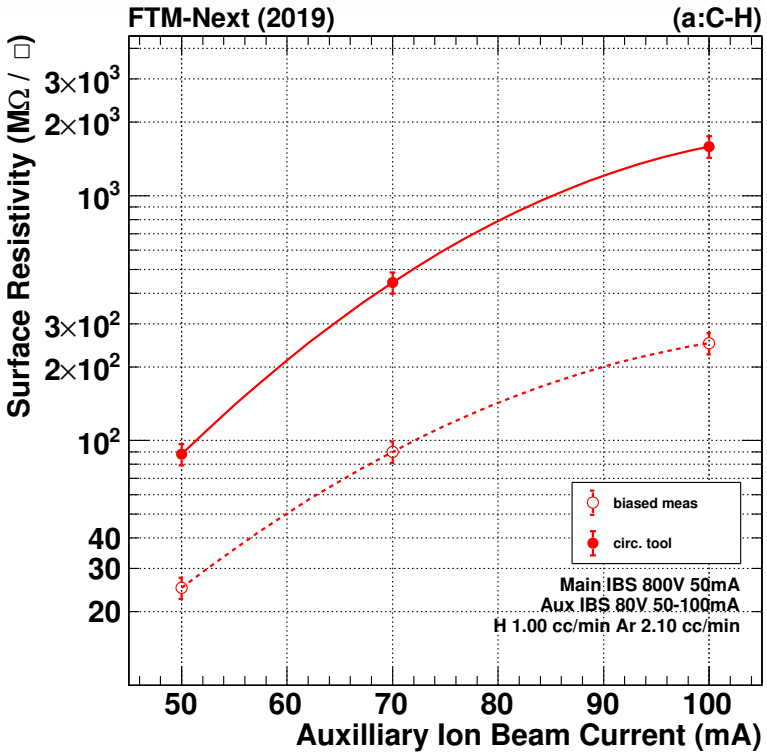


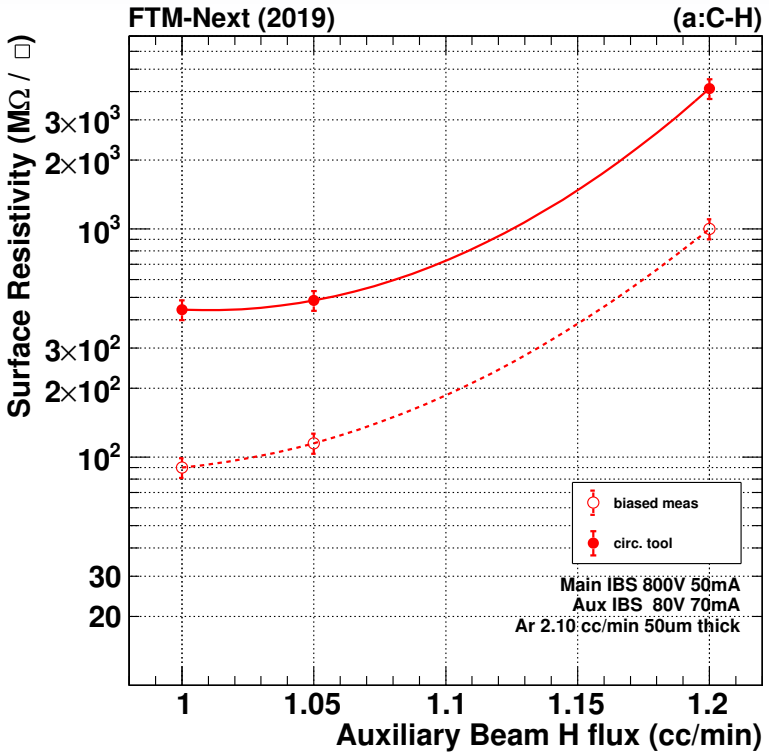
	1819	1820	1821	
Main Ion Beam	*Ar*	*Ar*	*Xe*	
	2.5 cc/min	2.5 cc/min	2.5 cc/min	
	1200 eV	1200 eV	1200 eV	
	80 mA	60 mA	60 mA	
Aux Ion Beam	*Ar*	*Ar*	*Ar*	*N●*
	7 cc/min	7 cc/min	5 cc/min	2 cc/min
	60 eV	100 eV	50 eV	
	0.5 A	1.17 A	0.22 A	
	all time	first 5 nm	all time	

Time Evolution



Hydrogen doped DLC

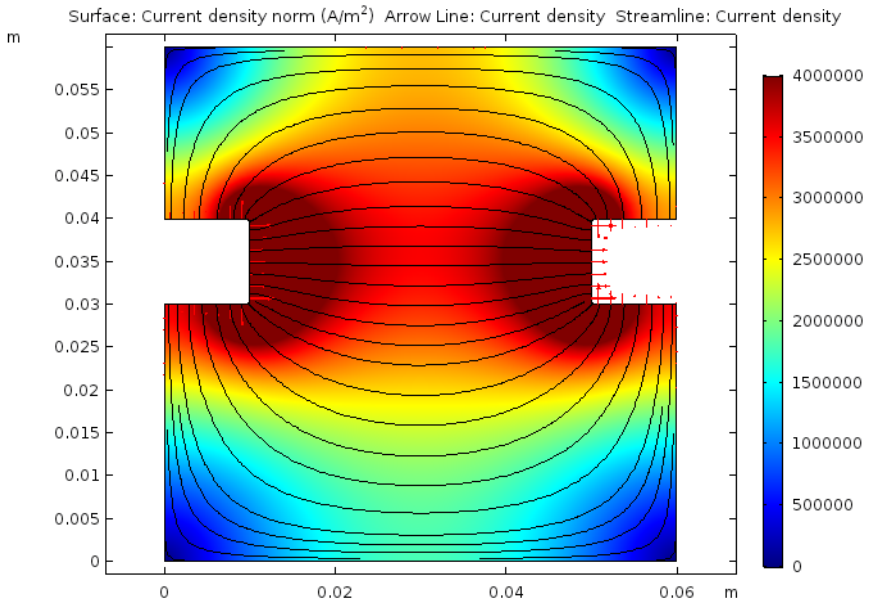




- IBS has many parameters, now: **AUX IBS current** & **gas concentration**
- Converge to 100 MΩ/□ . . . but measurement was biased
- **Next steps:** coat with Cr (5 nm) and Cu (100 nm) and try **etching**

Resistivity Simulations

Current Density $[A/m^2]$



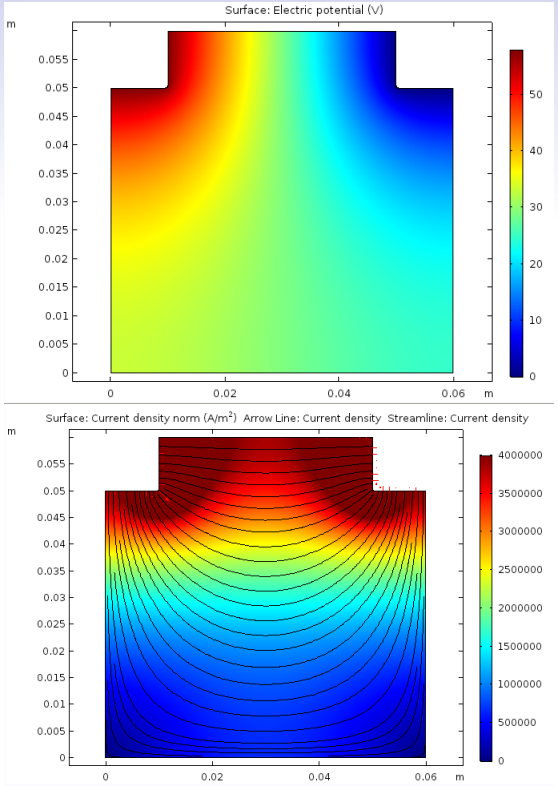
- Resistive coating of $D \times L \times t$ (thick)
- Application of 58 V potential difference
- Calculation of Potential $[V]$ and Current Density J $[A/m^2]$
- Determine the current through the electrodes by integration of J on the contours of the electrodes:

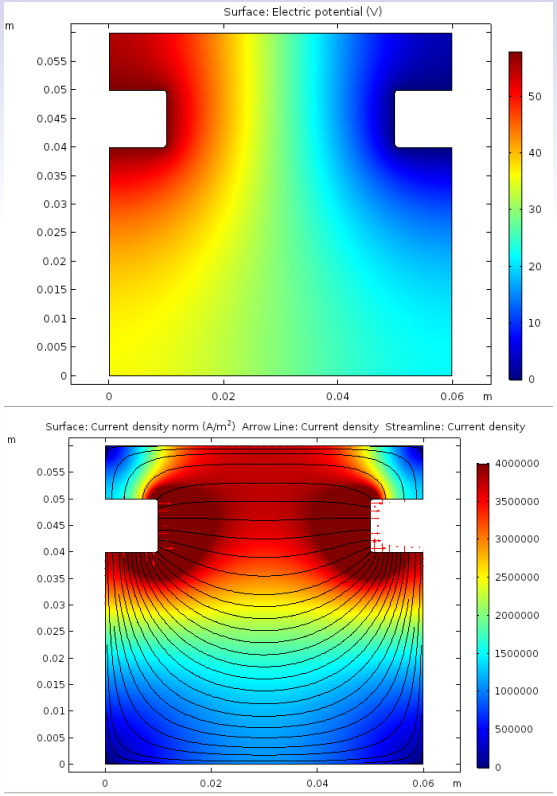
$$I_s = \oint_{\mathcal{C}} J d\ell$$

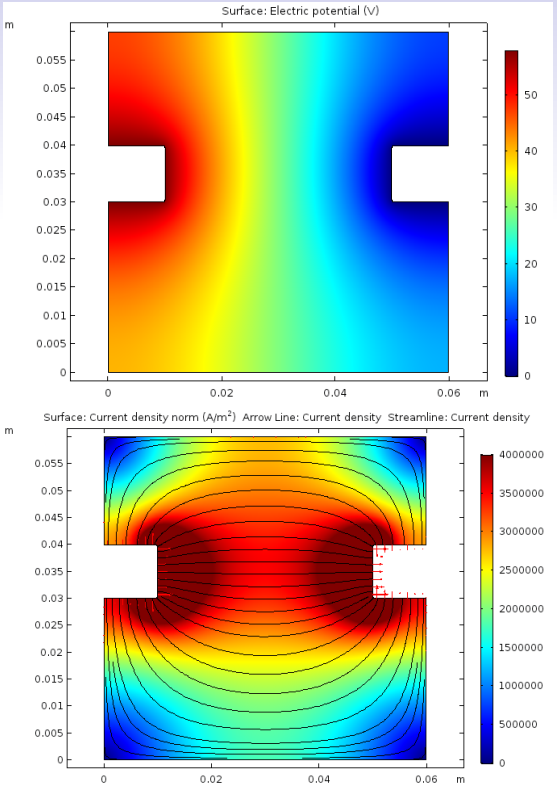
- 2D Simulation with infinitesimal thickness of the coating $\Rightarrow$ $I = I_s \times t$

- Resistance R $[\Omega]$, resistivity ρ $[\Omega \cdot m]$: $R = \rho \frac{L}{D \cdot t}$
- Sheet Resistance R_s / surface resistivity ρ_s $[\Omega/\square]$:

$$R_s = \rho_s = \frac{\rho}{t} \qquad \& \qquad R_s = \rho_s = \frac{\Delta V / L}{I / D} = \frac{D}{L} \cdot \frac{\Delta V}{I}$$





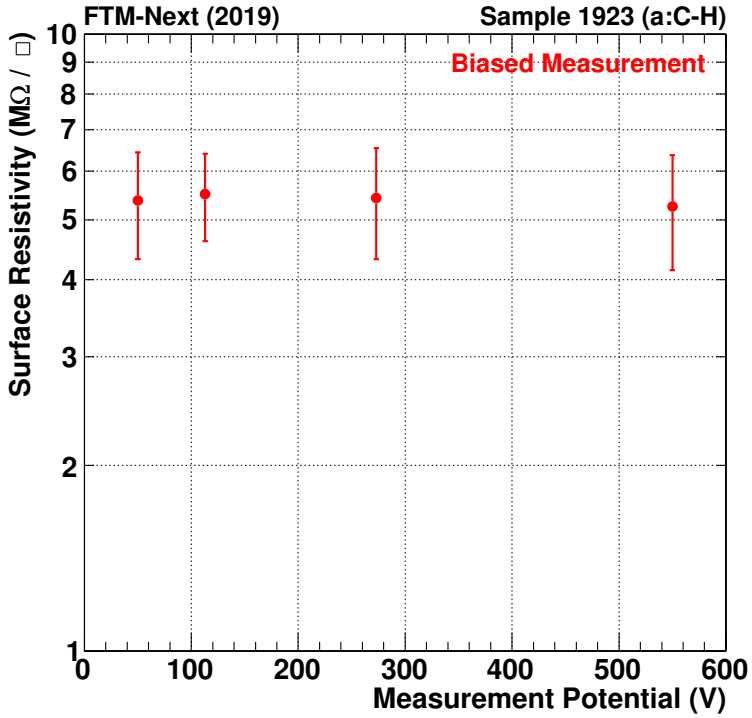


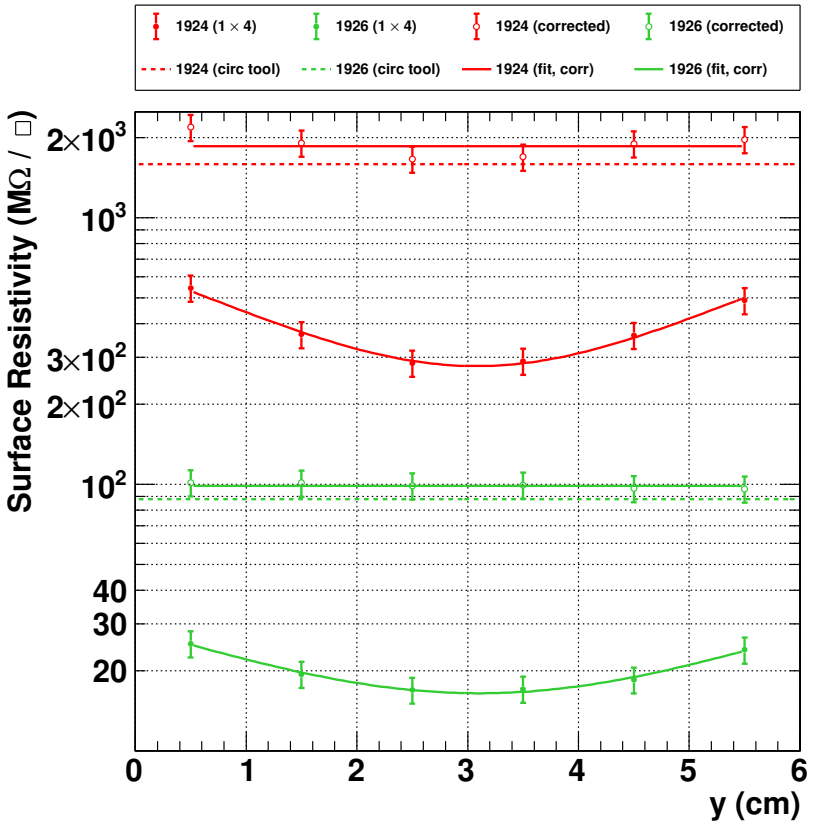
		I_s [A/m]	t [nm]	I [A]	$\Delta V/I$ [Ω]	D/L [-]	$\langle \rho_s \rangle$ [Ω/□]	correction [ref/est]
1 cm	graphite	115528 ± 8	100	11.55 mA	5021.65	1/4	1.255 k	2.65
	diamond-like	3.8509 ± 0.0001	100	0.385 μA	150.65 M	1/4	37.66 M	2.65
2 cm	graphite	150226 ± 7	100	15.02 mA	3861.51	1/4	0.965 k	3.45
	diamond-like	5.0075 ± 0.0002	100	0.501 μA	115.77 M	1/4	28.94 M	3.45
3 cm	graphite	167561 ± 7	100	16.76 mA	3460.62	1/4	0.865 k	3.85
	diamond-like	5.5854 ± 0.0002	100	0.559 μA	103.76 M	1/4	25.94 M	3.85

Application of Simulation Corrections

(left) **Resistive behaviour of a-C:H films**

(bottom) **Uniformity of a-C:H films**





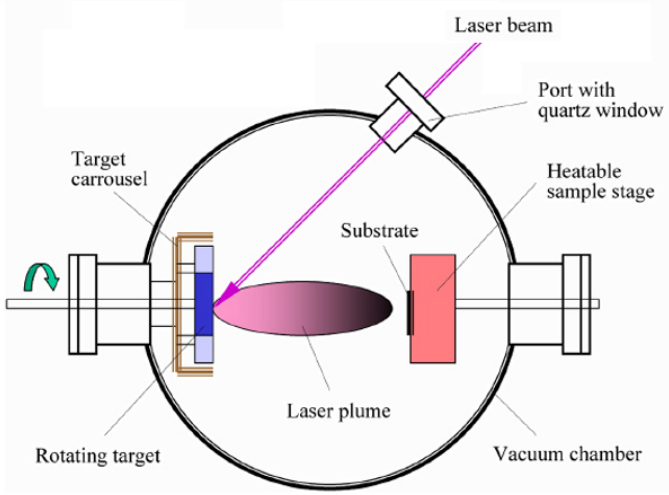
Pulsed Laser Deposition

Experimental Setup at INFN Lecce:

- multi-gas eximer laser
  - 248 nm - 193 nm
  - 1-20 Hz (20 ns)
  - 400 mJ $\rightarrow 1 - 6\ \mathrm{J/cm^2}$
- vacuum chamber with computer controlled movable substrate holder (can rotate)
- Atomic Force Microscopy (AFM - roughness)
- Four-Point Probe Station (VDP - Resistivity)
- Raman & X-ray spectroscopy (σ - sp^3/sp^2)
- Scanning Electron Micro (SEM - sp^3/sp^2)

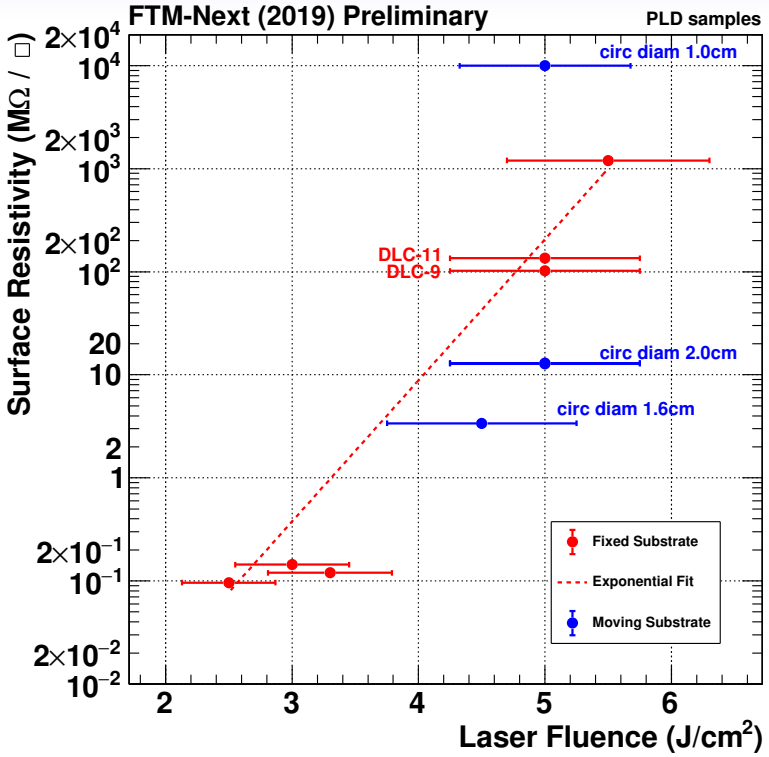
First depositions:

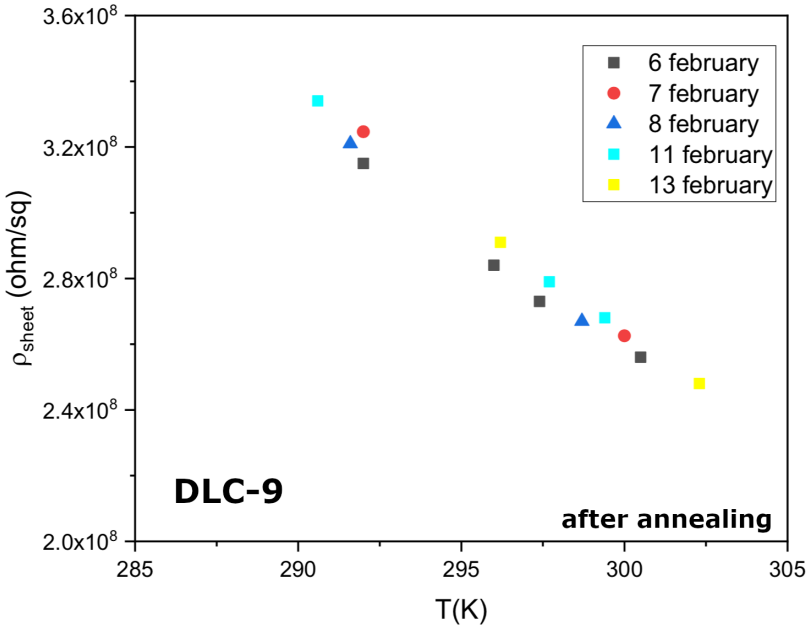
- varying Fluence (J) to tune resistivity
- Raman to determine sp_3/sp_2 ratio

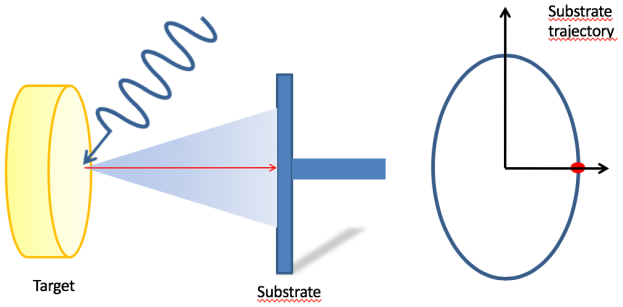


DLC produced through PLD

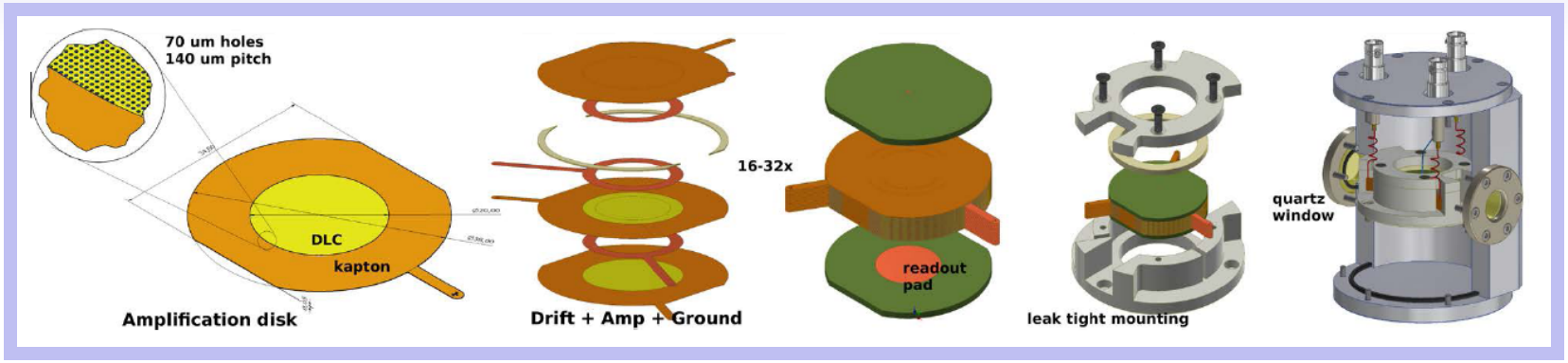
- (top L) Resistivity tuned by Fluence
- (top L) Target 100 MΩ/□ reached
- (bot L) PLD deposited samples stable in time
- (bot R) Substrate rotation ⇒ Uniformity
- (future) Further characterization ongoing (Raman, XPS, AFM)

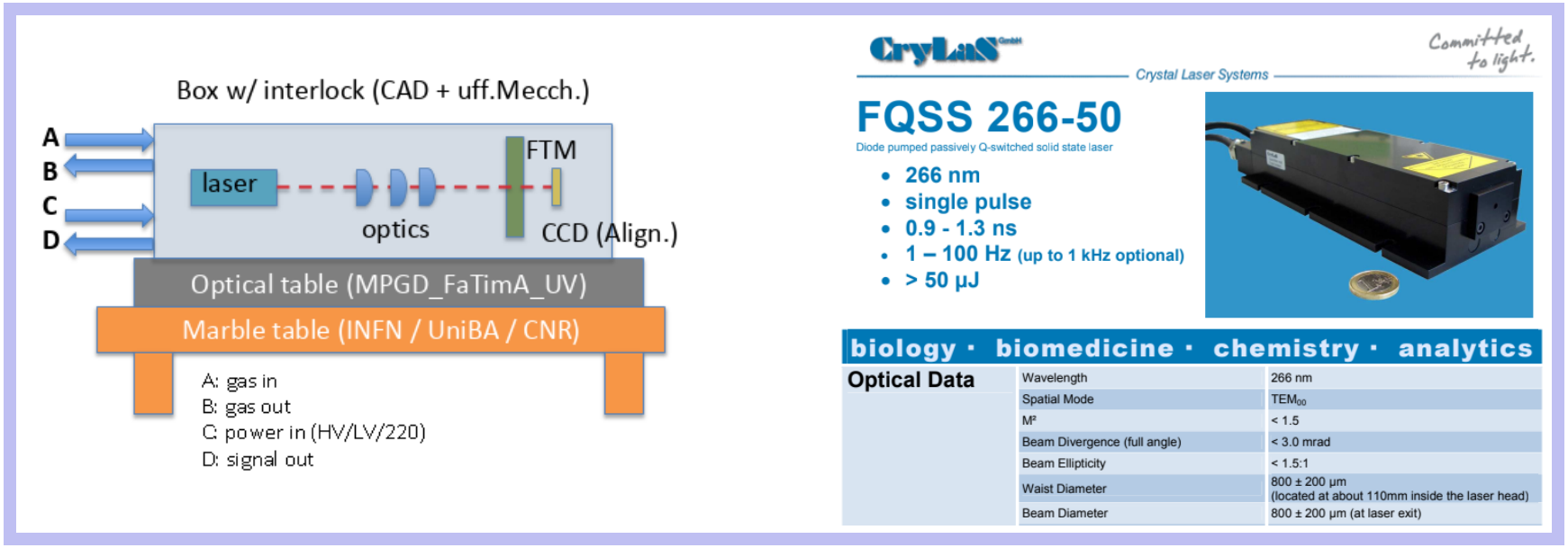






Future: Detector Construction & Tests





Summary

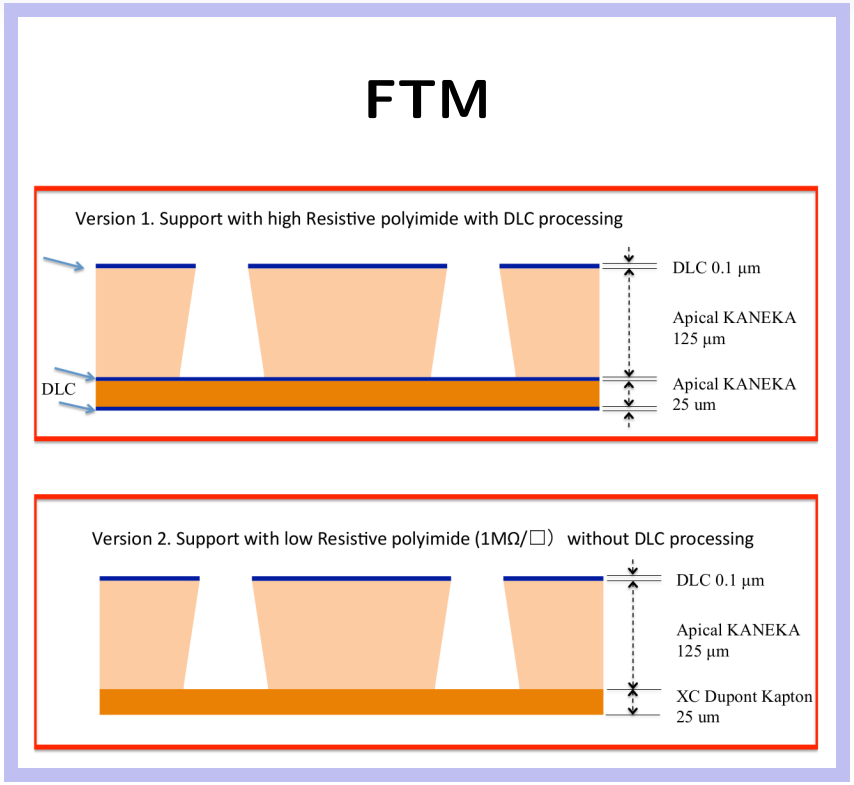
- Production problems DLC-coated PI films ⇒ understand better the DLC
- **Research collaboration established** in INFN between solid-state scientists and MPGD scientists & linked to the RD-51 *Resistive Collaboration*
- Hydrogen-doped DLC (6 cm × 6 cm) produced through **Ion Beam Deposition** and **resistivity** can be tuned from **10 to 1000 MΩ/□**
- DLC (3 cm × 3 cm) produced through **Pulsed Laser Deposition** ongoing, and **resistivity** can be varied from **100 kΩ/□ to 10 GΩ/□**
- Detailed characterization: DLC quality, sp^3/sp^2, internal stress, . . . ongoing
- **Next steps: etching** of samples of both technologies & detector prod and test
- Workshop on Resistive Coatings for Gaseous Detectors next week in Bari May 13-14, **indico.infn.it/e/rcgd19**

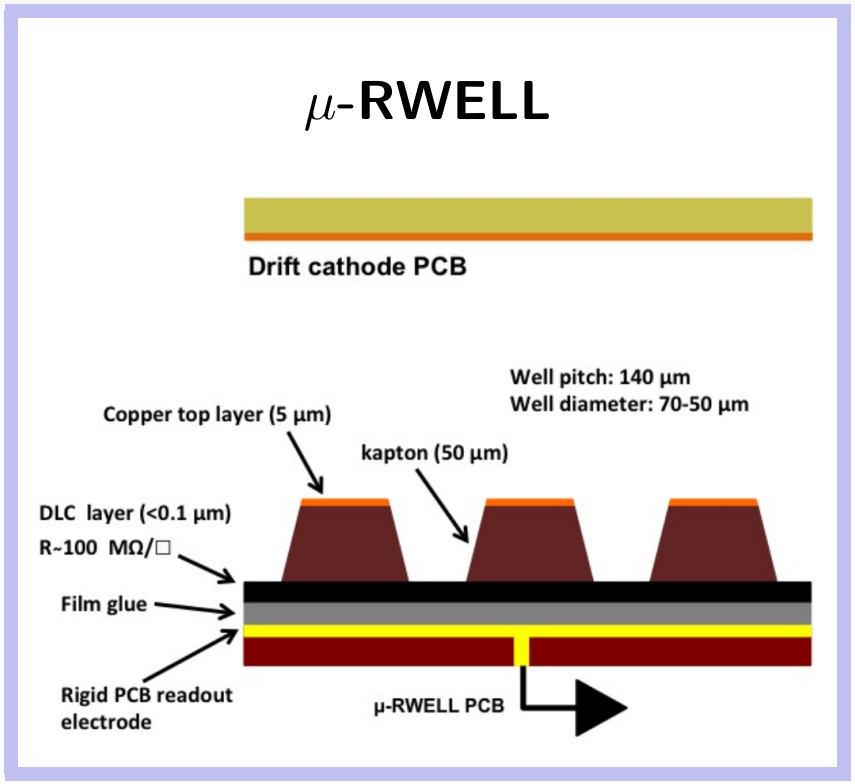
May 13-14, Bari, Italy
International Workshop on Resistive Coatings for Gaseous Detectors
RCGD

Backup:

- Amplification Structures
- FTM-v1 Results
- Derivation of FTM Formula
- Toy Monte-Carlo simulation
- Ion Beam Sources & Samples

Amplification Structure: Resistive μ-WELLs

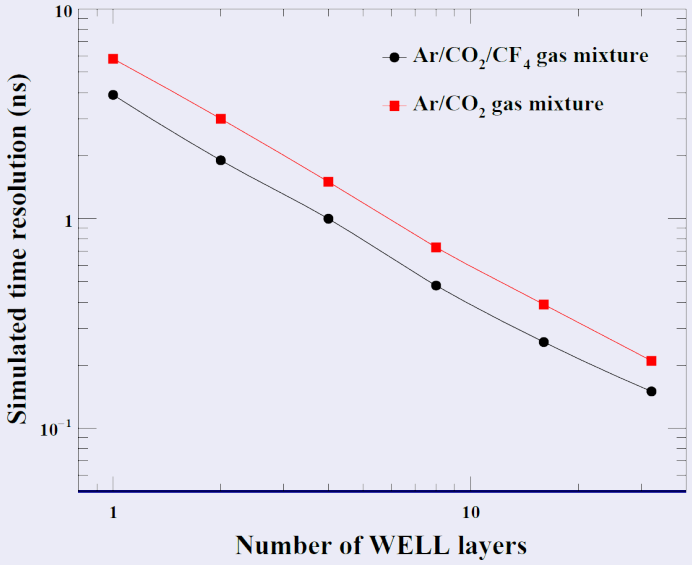




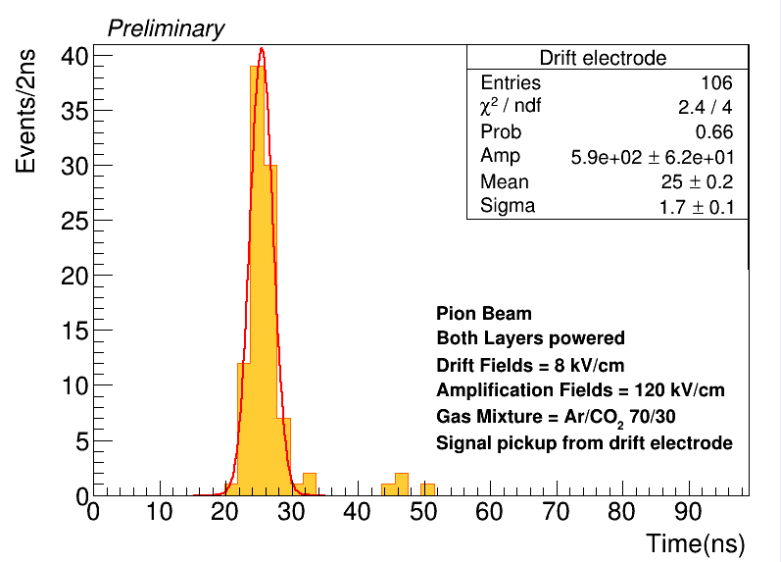
- By constr: FTM *inverted* hole (50-70 μm), μ-RWELL *normal* hole (70-50 μm)
- **Electric Field** calculation in gas **very similar** (independent of base details)
- FTM (multip. layers) $\Rightarrow$ micro-gap (250 μm); while 3–4 mm drift for μ-RWELL

First FTM Prototype (FTM-v1) :: Results

Simulations & SPS Test-beam Results [M. Maggi & I. Vai]



[source: arXiv:1503.05330]



[source: NIM A 845 (2017) 313]

- Simulations show time resolution decreasing for increasing number of layers
- Pion Test Beam for 2 layer prototype shows time resolution of 1.7±0.1 ns
- Muon Test Beam for 2 layer prototype shows time resolution of 2.4±0.1 ns
- $\sigma_t = 1/(\lambda v_{\text{drift}} N)$ with $\lambda^{\text{MIP}}_{\text{Ar/CO}_2\ 70/30} = 25\,\text{cm}^{-1}$, $v_{\text{drift}} = 8\,\text{cm}/\mu\text{s}$, $N = 2 \Rightarrow \sigma_t = 2.5\,\text{ns}$

Derivation of Fast Timing MPGD formula (I)

- Mean Free Path for Ionisation, with N being the electron density and σ_I the ionisation cross section:
$$\lambda = (N\sigma_I)^{-1}$$
- Number of encounters (= primary ionization or cluster density) n_p along path of length ℓ has a mean $\langle n_p \rangle = \nu = \ell/\lambda$ and is Poisson distributed:
$$P(\nu, k) = \frac{\nu^k}{k!} \exp(-\nu)$$
- Then as a consequence the probability distribution $f(\ell)\,\mathrm{d}\ell$ of the free flight paths ℓ between the encounters is an exponential:
$$f(\ell)\,\mathrm{d}\ell = \frac{1}{\lambda} \exp(-\ell/\lambda)\,\mathrm{d}\ell$$
  - because the probability of finding zero encounters in the interval ℓ times the probability of one encounter in $\mathrm{d}\ell$ is equal to
$$\begin{aligned} f(\ell)\,\mathrm{d}\ell &= P(\ell/\lambda, 0) \times P(\mathrm{d}\ell/\lambda, 1) \\ &= \exp(-\ell/\lambda) \times \mathrm{d}\ell/\lambda \exp(-\,\mathrm{d}\ell/\lambda) \\ &= (1/\lambda)\exp(-\ell/\lambda)\,\mathrm{d}\ell \qquad \lim_{\mathrm{d}\ell \to 0} \exp(-\,\mathrm{d}\ell) = 1 \end{aligned}$$

based on Blum, Riegler, Rolandi, chapter 1

Derivation of Fast Timing MPGD formula (II)

- $\forall$ layer i, the distance between the amplification structure and the first ionisation cluster is exponential distributed: $P(X) = 1/\lambda_i \exp(-x/\lambda_i)$
- therefore the mean distance between the amplification structure and the first ionisation cluster is λ_i and the standard deviation is λ_i
- hence the response time is $\Delta_t = \lambda_i/v_d$ and the time resolution is $\sigma_t = \lambda_i/v_d$
- the distribution of the minimum of N exponentially distributed variables X_i is again an exponential distribution Y: $P(Y) = \sum(1/\lambda_i)\exp(-x\sum 1/\lambda_i)$
- $\forall i : \lambda_i = \lambda \quad \Rightarrow \quad \sum_{i=1}^{N} 1/\lambda_i = N/\lambda$
- therefore the minimum distance in a system of N layers is distributed by $P(Y) = (N/\lambda)\exp(-xN/\lambda)$
- the mean minimum distance is now λ/N, with standard deviation λ/N
- therefore the response time of the N-layer system is $\Delta_t = \lambda/(Nv_d)$ and the time resolution is $\sigma_t = \lambda/(Nv_d)$
- writing in terms of number of clusters per mm: $\nu = \lambda^{-1} \Rightarrow \sigma_t = (N\nu v_d)^{-1}$

Characteristics of Exponential Distributions

- The minimum of exponentially distributed variables follows again an exponential distribution:

$$Y = min(X_1, X_2, \ldots X_n) \text{ and } P(x_i) = \lambda_i exp(-\lambda_i x_i)$$

$$\Rightarrow \; P(y) = \sum \lambda_i exp(-\sum \lambda_i y)$$

- *used for FTM formula*
- The sum of exponentially distributed variables follows a Gamma distribution:

$$Y = \sum X_i \text{ and } P(x_i) = \lambda exp(-\lambda x_i)$$

$$\Rightarrow \; p(y) = \frac{(\lambda x)^{(n-1)}}{(n-1)!} \lambda exp(-\lambda x)$$

- *used for distribution of* 2nd *to* n^{th} *cluster position* *cfr.* **CERN-77-09**

Proof :: min of Exp Distr is Exp Distributed

Theorem If $X_i \sim \text{exponential}(\lambda_i)$, for $i = 1, 2, \ldots, n$, and $X_1, X_2, \ldots, X_n$ are mutually independent random variables, then

$$\min\{X_1, X_2, \ldots, X_n\} \sim \text{exponential}\left(\sum_{i=1}^{n} \lambda_i\right).$$

Proof The random variable X_i has cumulative distribution function

$$F_{X_i}(x) = P(X_i \leq x) = 1 - e^{-\lambda_i x_i} \qquad x > 0$$

for $i = 1, 2, \ldots, n$. Let the random variable $Y = \min\{X_1, X_2, \ldots, X_n\}$. Then the cumulative distribution function of Y is

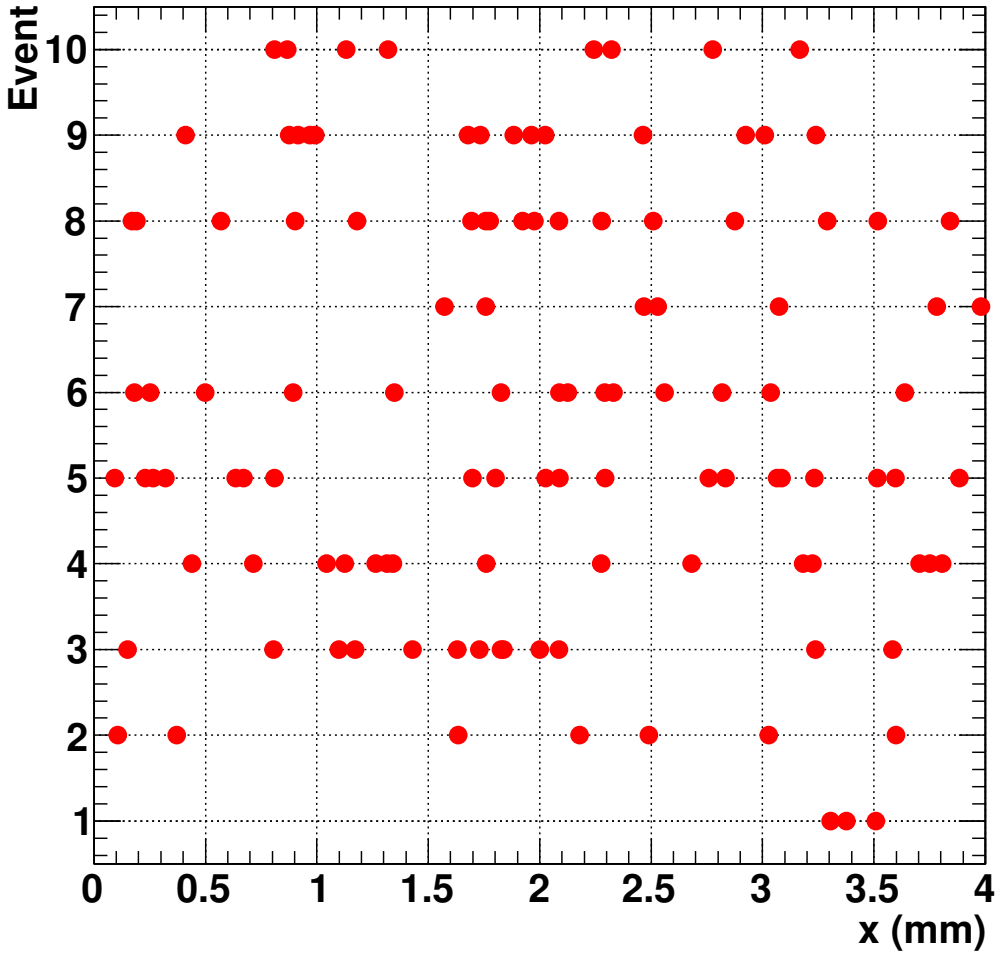
$$\begin{aligned}
F_Y(y) &= P(Y \leq y) \\
&= 1 - P(Y \geq y) \\
&= 1 - P(\min\{X_1, X_2, \ldots, X_n\} \geq y) \\
&= 1 - P(X_1 \geq y, X_2 \geq y, \ldots, X_n \geq y) \\
&= 1 - P(X_1 \geq y)\, P(X_2 \geq y) \ldots P(X_n \geq y) \\
&= 1 - e^{-\lambda_1 y} e^{-\lambda_2 y} \ldots e^{-\lambda_n y} \\
&= 1 - e^{-\lambda_1 y - \lambda_2 y - \cdots - \lambda_n y} \\
&= 1 - e^{-\sum_{i=1}^{n} \lambda_i y} \qquad y > 0.
\end{aligned}$$

This cumulative distribution function can be recognized as that of an exponential random variable with parameter $\sum_{i=1}^{n} \lambda_i$.

www.math.wm.edu/~leemis/chart/UDR/PDFs/ExponentialM.pdf

Toy Monte-Carlo Simulation (I)

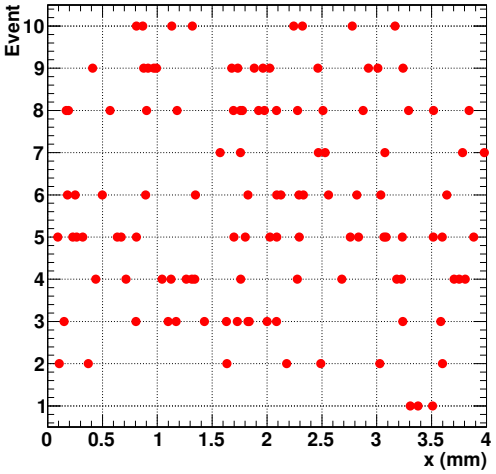
Simulate Primary Ionizations in 4 mm of gas. Distance between two ionisation encounters is modelled with an exponential distribution.



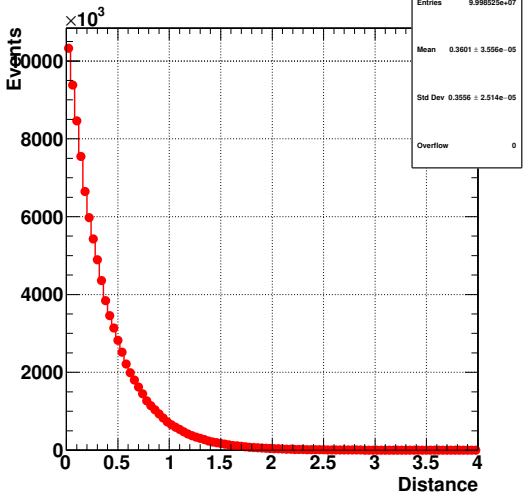
Event display for 10 Events

Toy Monte-Carlo Simulation (I)

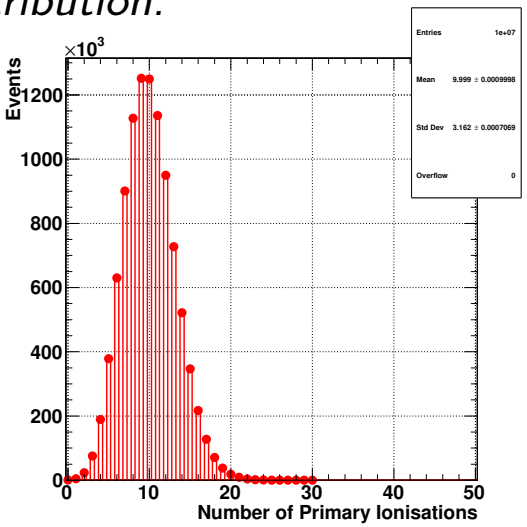
Simulate Primary Ionizations in 4 mm of gas. Distance between two ionisation encounters is modelled with an exponential distribution.



Event display for 10 Events



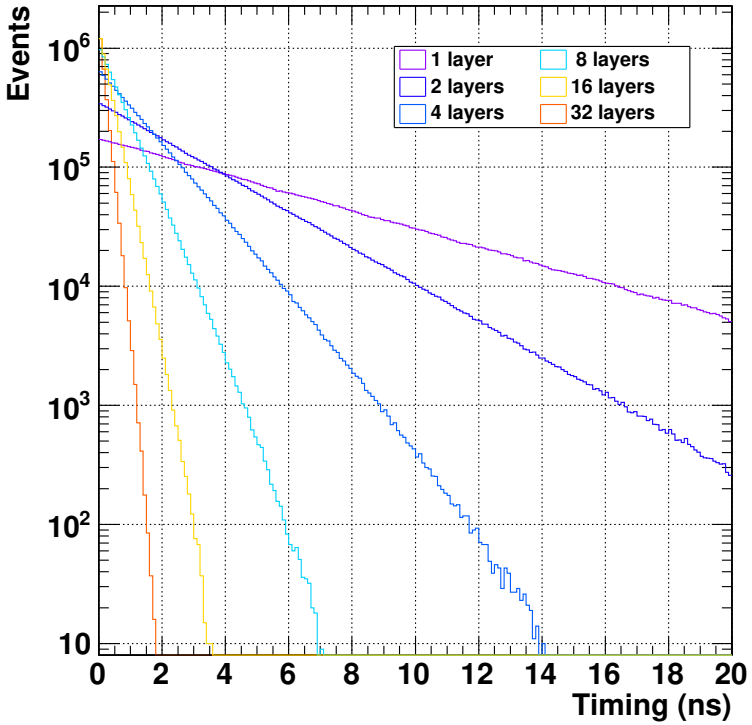
Distance is Exponentially distributed



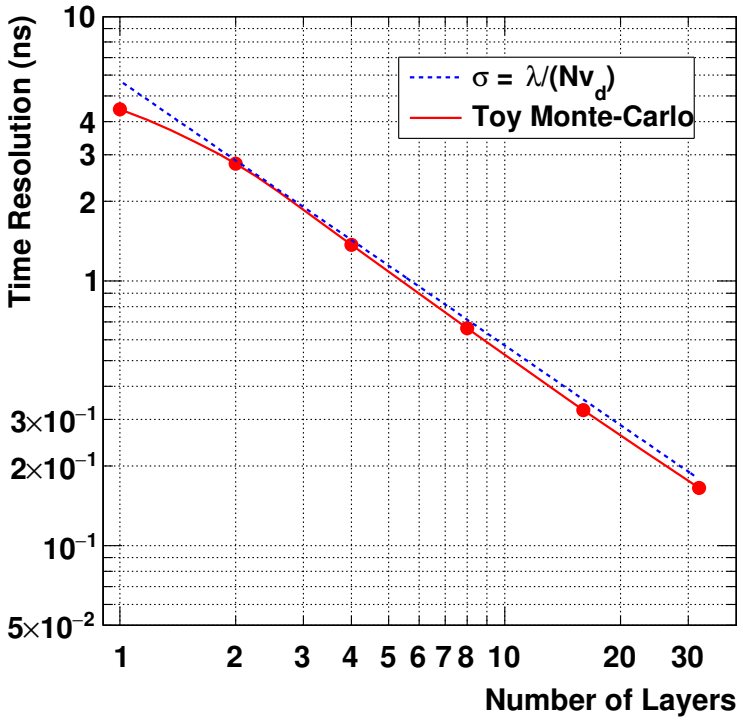
Number of Ionisations is Poisson distributed

Toy Monte-Carlo Simulation (II)

Slice 4 mm drift volume of gas in 2–32 layers and calculate drift time for each ionization to boundary of the layer. Drift Velocity of electrons in Ar:CO_2 (70:30) is 70 μm/ns for 3 kV/cm.



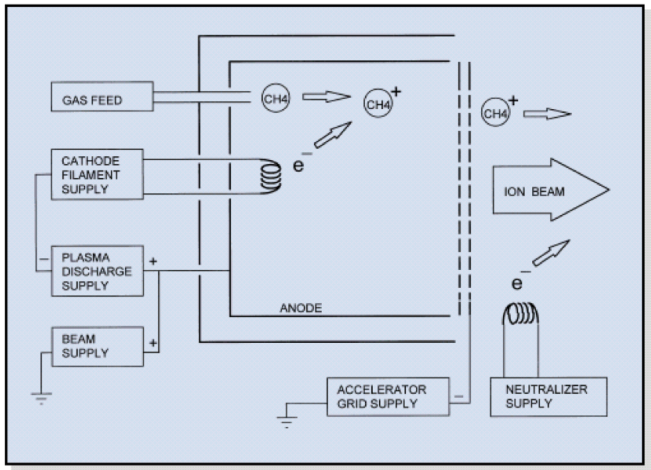
Arrival Time for all events in 2–32 layers



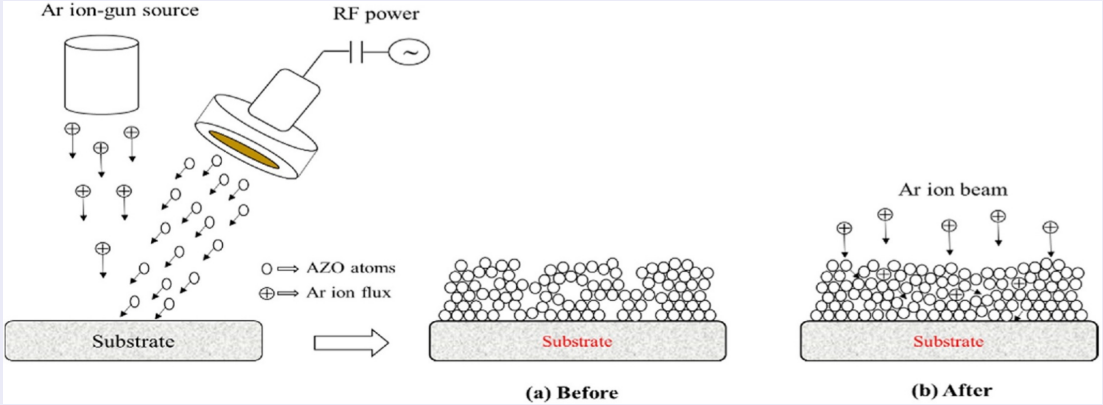
Time Resolution (σ) vs number of layers

Ion Beam sources

- Ion Beam Sources ⌀ 3 cm
- Tungsten filament & double grid for extraction
- **Main beam:** high energy, low current
- **Assistant:** low energy, high current
  - clean substrate before deposition (remove organic components)
  - passivate surface during deposition
  - augments ion mobility, leading to higher uniformity films



Assistance Ion Beam



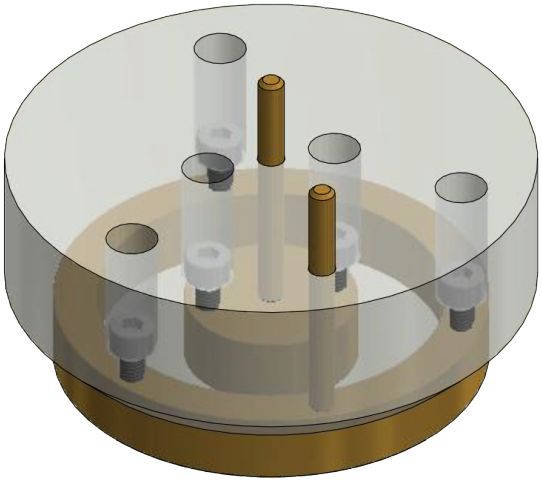
A.Sreedhar et al. Materials Research Bulletin 95 (2017) 451-458

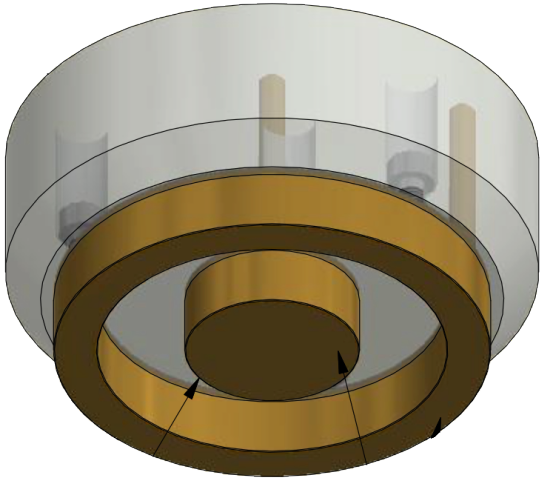
Ion Beam DLC Deposition Parameters

Number	1	2	3
Sample	1819	1820	1821
Pre-Treatment	$O\bullet$	$O\bullet$	$Ar\bullet$
	10 cc/min	10 cc/min	10 cc/min
	900 s	300 s	300 s
	0.5 A	0.7 A	2.6 A
	100 eV	100 eV	100 eV
Main Ion Beam	Ar	Ar	Xe
	2.5 cc/min	2.5 cc/min	2.5 cc/min
	1200 eV	1200 eV	1200 eV
	80 mA	60 mA	60 mA
Aux Ion Beam	Ar	Ar	Ar $N\bullet$
	7 cc/min	7 cc/min	5 cc/min 2 cc/min
	60 eV	100 eV	50 eV
	0.5 A	1.17 A	0.22 A
	all time	first 5 nm	all time
Doping	-	-	$N\bullet$
			2 cc/min
Thickness	100 nm	100 nm	100 nm
Deposition Time	3600 s	2700 s	4500 s
	60 min	45 min	75 min

Circular Tool

Construction of circular tool



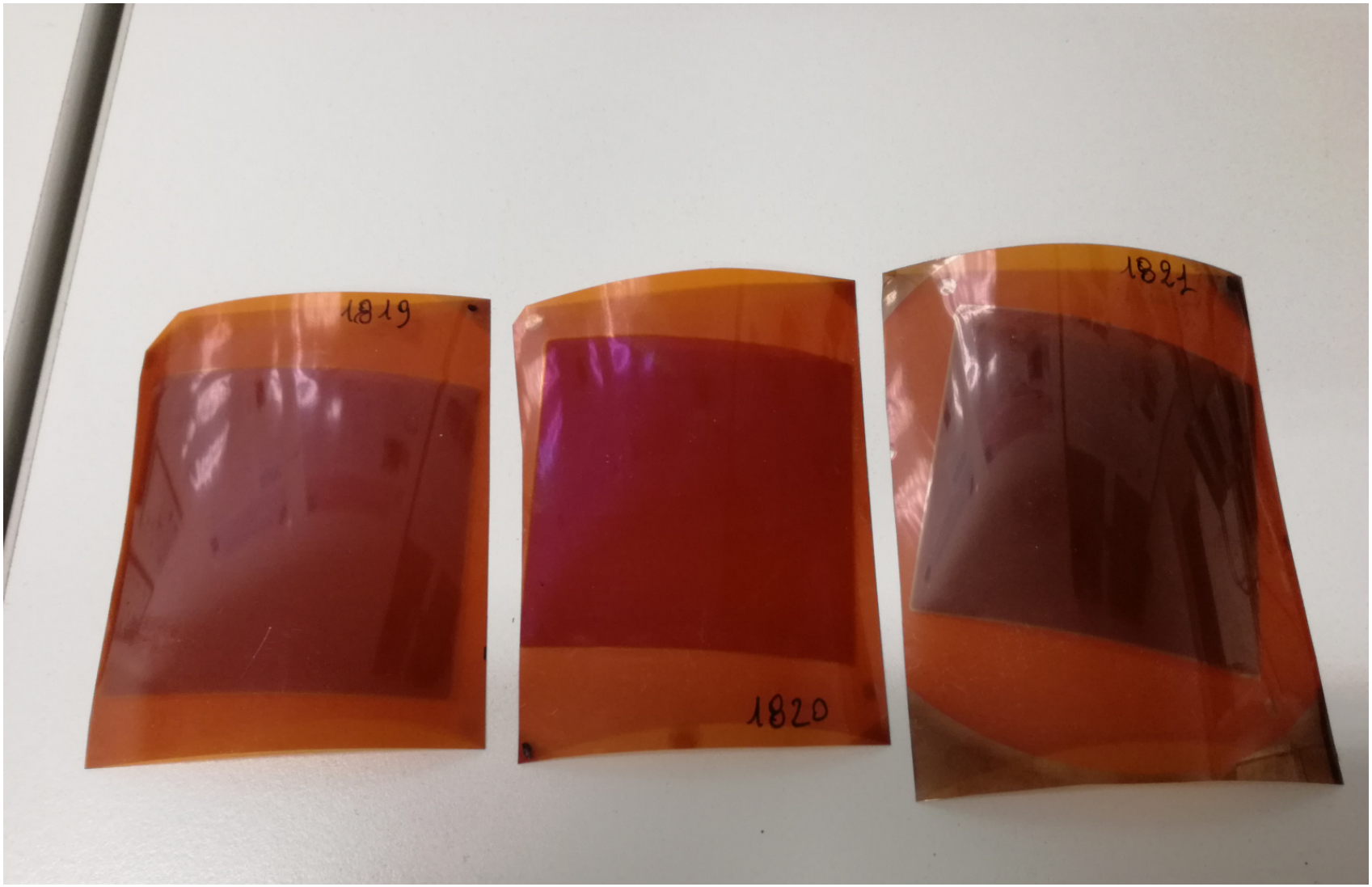


Radii: $r_1 = 1\,\text{cm}$ & $r_2 = 2\,\text{cm}$

$$\rho_s = R \cdot \frac{2\pi}{\ln(r_2/r_1)} = \frac{\Delta V}{I} \cdot \mathbf{9.0647} \tag{1}$$

Ion Beam Deposition Samples

1819 – 1820 – 1821



Pulsed Laser Deposition Samples