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)
Fast Timing MPGD Principle

**Traditional MPGD**

- \( \sigma_t \) driven by distance fluct's
  \[ \sigma_t \propto \frac{1}{(\lambda v_{\text{drift}})} \]
  \( \lambda \) = # 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

- \( \sigma_t \propto \frac{1}{(\lambda v_{\text{drift}}N)} \)

**Choice of Resistivity**

- 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 for the Fast Timing MPGD
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 sp³ fraction, size and concentration of sp² sites and hydrogen content
- Wide range of applications: reduce abrasive wear & friction, engines, Hard Disks, medical app, beer, . . .

See also talk Lunlin Shang - Thu 9/05
**Motivation**

**Ion Beam Sputtering**

**Resistivity Simulations**

**Pulsed Laser Deposition**

**Summary**

**Backup**

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**Fast Timing MPGD**

**polyimide prototype**

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

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**Single layer specifications:**

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

- Garfield & COMSOL sims validated (μRWELL data); reach G ∼ 5000 at 500 V
- Toy Monte-Carlo ⇒ ionisation eff & timing for 250 μm gaps (Ar:CO₂ 70:30)
- SPICE simulations for signal transparency of different layers ongoing

Diamond Like Carbon for the Fast Timing MPGD
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: $O(0.1 \text{ eV})$ sputter: $O(0.1–10 \text{ eV})$ ion beam $O(10–100 \text{ eV})$

- **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:**
  - $\lambda$ 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• / Ar• radicals
- Ion Beam Source (1 keV, 100 mA)
- Assistant Source (100 eV, 1 A)
- Graphite Target: ∅10 cm
- Substrate: 6 × 6 cm²
- Quartz balance → film thickness
- Deposition speed ∼ 100 nm / hour

First samples in Dec 2018;
Followed with a few attempts with N₂ doping and many with H₂ doping 2019
Ion-beam sputtering Setup

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

**Motivation**

- Ion Beam Sputtering
- Resistivity Simulations
- Pulsed Laser Deposition
- Summary

**Backup**

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**Resistivity Measurements**

**Uniformity (3–5%)**

<table>
<thead>
<tr>
<th>Measurement 1</th>
<th>Measurement 2</th>
<th>Measurement 3</th>
<th>Measurement 4</th>
<th>Measurement 5</th>
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</thead>
</table>

Surface Resistivity (MΩ/□)

- **1819 (6 x 1)**
- **1820 (6 x 1)**
- **1821 (6 x 1)**

**Diamond Like Carbon for the Fast Timing MPGD**
Resistivity Measurements

<table>
<thead>
<tr>
<th></th>
<th>1819</th>
<th>1820</th>
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<tbody>
<tr>
<td><strong>Main Ion Beam</strong></td>
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<tr>
<td>Ar</td>
<td>2.5 cc/min</td>
<td>2.5 cc/min</td>
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<tr>
<td>1200 eV</td>
<td>1200 eV</td>
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<tr>
<td>80 mA</td>
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<td><strong>Aux Ion Beam</strong></td>
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<tr>
<td>Ar</td>
<td>7 cc/min</td>
<td>7 cc/min</td>
<td>5 cc/min</td>
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<tr>
<td>60 eV</td>
<td>100 eV</td>
<td>50 eV</td>
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<tr>
<td>0.5 A</td>
<td>1.17 A</td>
<td>0.22 A</td>
<td></td>
</tr>
<tr>
<td>all time</td>
<td>first 5 nm</td>
<td>all time</td>
<td>all time</td>
</tr>
</tbody>
</table>

Diamond Like Carbon for the Fast Timing MPGD
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

- Resistive coating of $D \times L \times t$ (thick)
- Application of 58 V potential difference
- Calculation of Potential $[V]$ and Current Density $[A/m^2]$
- Determine the current through the electrodes by integration of $J$ on the contours of the electrodes:
  $$I_s = \oint_{C} J \, dl$$
- 2D Simulation with infinitesimal thickness of the coating $\Rightarrow I = I_s \times t$

- Resistance $R \, [\Omega]$, resistivity $\rho \, [\Omega \cdot m]$: $R = \rho \frac{L}{D \cdot t}$
- Sheet Resistance $R_s /$ surface resistivity $\rho_s \, [\Omega/\square]$:
  $$R_s = \rho_s = \frac{\rho}{t} \quad \& \quad R_s = \rho_s = \frac{\Delta V/L}{I/D} = \frac{D}{L} \cdot \frac{\Delta V}{I}$$

- Diamond Like Carbon for the Fast Timing MPGD
**Motivation**

**Ion Beam Sputtering**

**Resistivity Simulations**

**Pulsed Laser Deposition**

**Summary**

**Backup**

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**Motivation**

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<table>
<thead>
<tr>
<th>$l_s$</th>
<th>$t$</th>
<th>$I$</th>
<th>$\Delta V / I$</th>
<th>$D/L$</th>
<th>$\langle \rho_s \rangle$</th>
<th>correction</th>
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<tr>
<td>[A/m]</td>
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<td>[A]</td>
<td>[Ω]</td>
<td>[-]</td>
<td>[Ω/□]</td>
<td>[ref/est]</td>
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<td>1 cm graphite</td>
<td>115528 ± 8</td>
<td>100</td>
<td>11.55 mA</td>
<td>5021.65</td>
<td>1/4</td>
<td>1.255 k</td>
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<tr>
<td>diamond-like</td>
<td>3.8509 ± 0.0001</td>
<td>100</td>
<td>0.385 μA</td>
<td>150.65 M</td>
<td>1/4</td>
<td>37.66 M</td>
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<td>2 cm graphite</td>
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<td>15.02 mA</td>
<td>3861.51</td>
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<td>0.965 k</td>
</tr>
<tr>
<td>diamond-like</td>
<td>5.0075 ± 0.0002</td>
<td>100</td>
<td>0.501 μA</td>
<td>115.77 M</td>
<td>1/4</td>
<td>28.94 M</td>
</tr>
<tr>
<td>3 cm graphite</td>
<td>167561 ± 7</td>
<td>100</td>
<td>16.76 mA</td>
<td>3460.62</td>
<td>1/4</td>
<td>0.865 k</td>
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<tr>
<td>diamond-like</td>
<td>5.5854 ± 0.0002</td>
<td>100</td>
<td>0.559 μA</td>
<td>103.76 M</td>
<td>1/4</td>
<td>25.94 M</td>
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**Diamond Like Carbon for the Fast Timing MPGD**
Application of Simulation Corrections

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

(bottom) Uniformity of a-C:H films

Diamond Like Carbon for the Fast Timing MPGD
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 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 ($\sigma$ - 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)

Surface Resistivity (MΩ / □)

Laser Fluence (J/cm²)

FTM-Next (2019) Preliminary

DLC samples

DLC-9

after annealing

T(K)

ρ sheet (ohm/sq)

2.8x10⁸

2.4x10⁸

2.0x10⁸

3.2x10⁸

3.6x10⁸

2 3 4 5 6

2−10

2−10

1−10

1−10

2

10

20

310

410

×2

×2

×2

Fixed Substrate
Exponential Fit
Moving Substrate

Substrate trajectory
Future: Detector Construction & Tests

Box w/ interlock (CAD + uff.Mecch.)

A: gas in
B: gas out
C: power in (HV/LV/220)
D: signal out

Optical table (MPGD_FaTimA_UV)

Marble table (INFN / UniBA / CNR)

FQSS 266-50
Diode pumped passively Q-switched solid state laser
- 266 nm
- single pulse
- 0.9 - 1.3 ns
- 1 - 100 Hz (up to 1 kHz optional)
- > 50 μJ

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<th>chemistry</th>
<th>analytics</th>
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<td><strong>Optical Data</strong></td>
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<tr>
<td>Wavelength</td>
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<tr>
<td>Spatial Mode</td>
<td>TEM00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP</td>
<td>&lt; 1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Diameter (full angle)</td>
<td>&lt; 3.0 mrad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Ellipticity</td>
<td>= 1.5:1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waist Diameter</td>
<td>800 ± 200 μm (located at about 110 mm inside the laser head)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Diameter</td>
<td>800 ± 200 μm (at laser exit)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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, sp³/sp², 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](indico.infn.it/e/rcgd19)
Backup:

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

Ion Beam Sputtering

Resistivity Simulations

Pulsed Laser Deposition

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Amplification Structure: Resistive $\mu$-WELLs

- **FTM**
  - Version 1. Support with high Resistive polyimide with DLC processing
  - DLC 0.1 $\mu$m
  - Apical KANEKA 125 $\mu$m
  - Apical KANEKA 25 $\mu$m

- **$\mu$-RWELL**
  - Drift cathode PCB
  - Copper top layer (5 $\mu$m)
  - Well pitch: 140 $\mu$m
  - Well diameter: 70-50 $\mu$m
  - DLC layer (<0.1 $\mu$m)
  - R-100 M$\Omega$/□
  - Film glue
  - Rigid PCB readout electrode
  - $\mu$-RWELL PCB

- By constr: FTM *inverted* hole (50-70 $\mu$m), $\mu$-RWELL *normal* hole (70-50 $\mu$m)
- **Electric Field** calculation in gas *very similar* (independent of base details)
- FTM (multip. layers) $\Rightarrow$ micro-gap (250 $\mu$m); while 3–4 mm drift for $\mu$-RWELL
First FTM Prototype (FTM-v1) :: Results

Simulations & SPS Test-beam Results

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

Derivation of Fast Timing MPGD formula (I)

- Mean Free Path for Ionisation, with \( N \) being the electron density and \( \sigma_I \) the ionisation cross section:
  \[
  \lambda = (N\sigma_I)^{-1}
  \]

- Number of encounters (= primary ionization or cluster density) \( n_p \) along path of length \( \ell \) 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 \( f(\ell) \, d\ell \) of the free flight paths \( \ell \) between the encounters is an exponential:
  \[
  f(\ell) \, d\ell = \frac{1}{\lambda} \exp(-\ell / \lambda) \, d\ell
  \]
  because the probability of finding zero encounters in the interval \( \ell \) times the probability of one encounter in \( d\ell \) is equal to
  \[
  f(\ell) \, d\ell = P(\ell / \lambda, 0) \times P(d\ell / \lambda, 1)
  \]
  \[
  = \exp(-\ell / \lambda) \times d\ell / \lambda \exp(-d\ell / \lambda)
  \]
  \[
  = (1/\lambda) \exp(-\ell / \lambda) \, d\ell \quad \lim_{d\ell \to 0} \exp(-d\ell) = 1
  \]
Derivation of Fast Timing MPGD formula (II)

\[ \forall \text{ layer } i, \text{ the distance between the amplification structure and the first ionisation cluster is exponential distributed: } P(X) = \frac{1}{\lambda_i} \exp(-x/\lambda_i) \]

\[ \text{therefore the mean distance between the amplification structure and the first ionisation cluster is } \lambda_i \text{ and the standard deviation is } \lambda_i \]

\[ \text{hence the response time is } \Delta t = \frac{\lambda_i}{\nu_d} \text{ and the time resolution is } \sigma_t = \frac{\lambda_i}{\nu_d} \]

\[ \text{the distribution of the minimum of } N \text{ exponentially distributed variables } X_i \text{ is again an exponential distribution } Y: P(Y) = \sum (1/\lambda_i) \exp(-x \sum 1/\lambda_i) \]

\[ \forall i : \lambda_i = \lambda \Rightarrow \sum_{i=1}^{N} 1/\lambda_i = N/\lambda \]

\[ \text{therefore the minimum distance in a system of } N \text{ layers is distributed by } P(Y) = (N/\lambda) \exp(-xN/\lambda) \]

\[ \text{the mean minimum distance is now } \lambda/N, \text{ with standard deviation } \lambda/N \]

\[ \text{therefore the response time of the } N\text{-layer system is } \Delta t = \frac{\lambda}{(N\nu_d)} \text{ and the time resolution is } \sigma_t = \frac{\lambda}{(N\nu_d)} \]

\[ \text{writing in terms of number of clusters per mm: } \nu = \lambda^{-1} \Rightarrow \sigma_t = (N\nu\nu_d)^{-1} \]
Characteristics of Exponential Distributions

- The minimum of exponentially distributed variables follows again an exponential distribution:
  \[ Y = \min(X_1, X_2, \ldots, X_n) \text{ and } P(x_i) = \lambda_i \exp(-\lambda_i x_i) \]
  \[ \Rightarrow P(y) = \sum \lambda_i \exp(-\sum \lambda_i y) \]
  \textit{used for FTM formula}

- The sum of exponentially distributed variables follows a Gamma distribution:
  \[ Y = \sum X_i \text{ and } P(x_i) = \lambda \exp(-\lambda x_i) \]
  \[ \Rightarrow p(y) = \frac{(\lambda x)^{(n-1)}}{(n-1)!} \lambda \exp(-\lambda x) \]
  \textit{used for distribution of } 2^{nd} \text{ to } n^{th} \text{ cluster position} \quad \text{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

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

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

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

This cumulative distribution function can be recognized as that of an exponential random variable with parameter $\sum_{i=1}^{n} \lambda_i$. 
Toy Monte-Carlo Simulation (I)

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

Diamond Like Carbon for the Fast Timing MPGD
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 $\mu$m/ns for 3 kV/cm.

Arrival Time for all events in 2–32 layers

Time Resolution ($\sigma$) vs number of layers
Ion Beam sources

- Ion Beam Sources $\varnothing$ 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**

# Ion Beam DLC Deposition Parameters

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<th>Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
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<td>Sample</td>
<td>1819</td>
<td>1820</td>
<td>1821</td>
</tr>
<tr>
<td>O•</td>
<td>O•</td>
<td>Ar•</td>
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<td>60 eV</td>
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<td>0.5 A</td>
<td>1.17 A</td>
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<td>all time</td>
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</tr>
<tr>
<td></td>
<td>60 min</td>
<td>45 min</td>
<td>75 min</td>
</tr>
</tbody>
</table>
Circular Tool

Construction of circular tool

Radii: \( r_1 = 1 \text{ cm} \) & \( r_2 = 2 \text{ cm} \)

\[
\rho_s = R \cdot \frac{2\pi}{\ln \left( \frac{r_2}{r_1} \right)} = \frac{\Delta V}{I} \cdot 9.0647
\] (1)
Ion Beam Deposition Samples

1819 – 1820 – 1821
Pulsed Laser Deposition Samples