MEG II 実験背景事象削減のための高レート耐性RPCの高抵抗電極の開発 -設計と製作-

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(神戸大理，東大素セ[A]，東大理[B])

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Outline

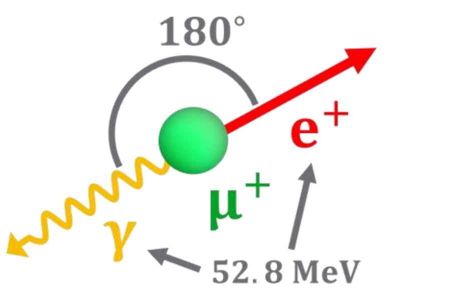
- Introduction
  - MEG II experiment
  - Radiative decay counter
  - RPC for upstream RDC
  - Status of studies with prototype
- Development of a new pillar structure
  - Problem of pillar formation
  - New strategy for obtaining sufficient gap
  - Alignment method
- Development of resistive electrode
  - Rate capability of RPC
  - Suppression of voltage drop
  - Determination of strip pitch
  - Implementation of HV supply
- Summary and prospect

MEG II experiment

- MEG II searches for $\mu^+ \rightarrow e^+\gamma$ decay
  - Charged lepton flavor violating decays

- Main Background source is **accidental coincidence of BG-e^+ and BG-γ**

Signal



The signal features are

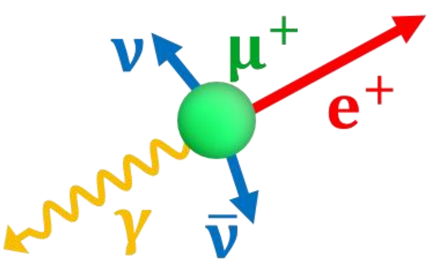
- The same **energy** (52.8 MeV)
- The same **timing**
- Opposite **direction**

Background event

Accidental coincidence of BG-e^+ and BG-γ with different sources

- Signal-like features

BG-γ source



Radiative muon decay (**RMD**)

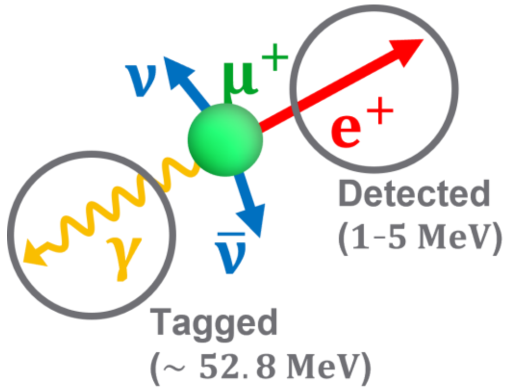
- One of BG-γ source

Annihilation in flight (AIF)

- Suppressed by lowering the material budget of the CDCH

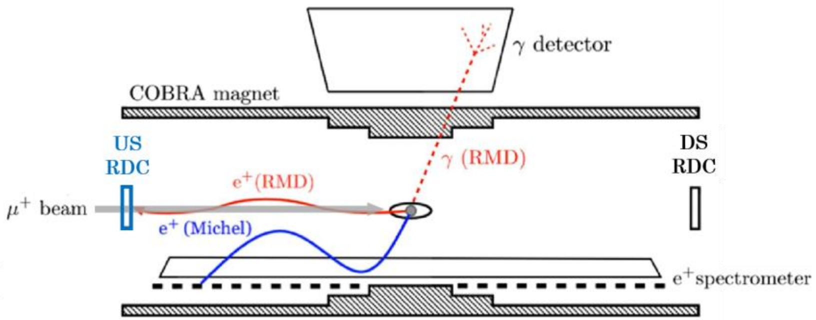
Radiative Decay Counter (RDC)

- Detector for tagging BG-γ
  - When BG-γ have a signal-like energy ($\sim 52.8\ \mathrm{MeV}$), most of e^+ have a low energy ($1\text{-}5\ \mathrm{MeV}$)
  - Downstream RDC has already been installed
  - **Upstream RDC is under development**



- Requirements to upstream RDC

1. Material budget: $< 0.1\%$ radiation length
   ➡ muon beam with $28\ \mathrm{MeV}/c$ must pass through the detector
2. Rate capability: $4\ \mathrm{MHz/cm^2}$ of muon beam
3. Radiation hardness: > 60 weeks operation
4. MIP efficiency: $> 90\%$
5. Timing resolution: $< 1\ \mathrm{ns}$
6. Detector size: $20\ \mathrm{cm}$ (diameter)



<u>Resistive Plate Chamber (RPC) with Diamond-Like Carbon (DLC) electrodes for upstream RDC</u>

RPC for upstream RDC

- **RPC** ➡ **Fast response** (< 1 ns)
- **DLC** ➡ **Controllable resistivity** (by changing film thickness)
  Small material budget (by sputtering directly onto thin polyimide films)

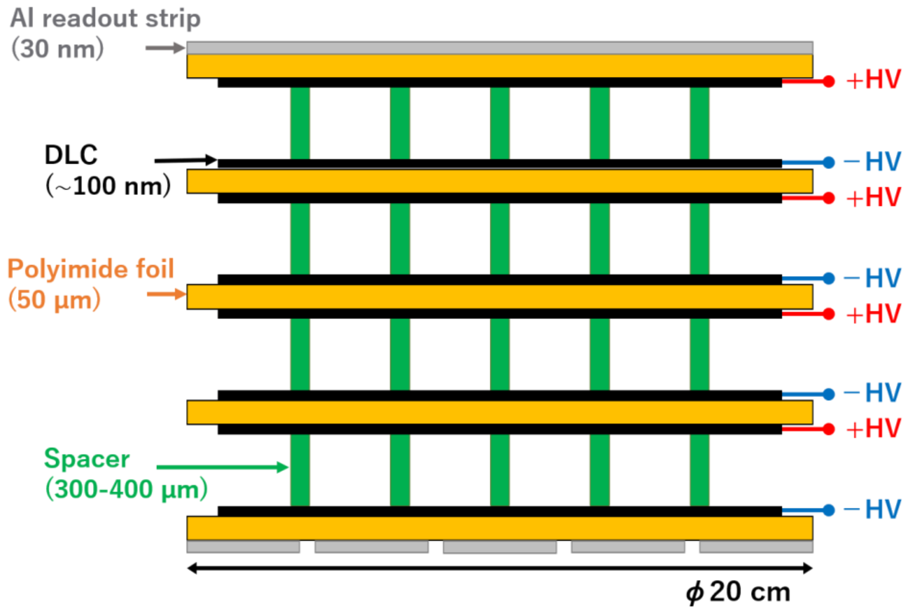
➢MEG II RPC design → **4-layer RPC**

Material budget

- Polyimide 50 μm → $0.018\%\ X_0$
- Aluminum 30 nm → $0.0034\%\ X_0$

➡ **0.095% radiation length**

Achieved $< 0.1\%$ radiation length



Status of studies with prototype

➢ Previous research reports with **3 cm × 3 cm prototype RPC**

MIP Efficiency

- The n-layers RPC efficiency is

$$\epsilon_n = 1 - (1 - \epsilon_1)^n \qquad \epsilon_n\text{: n-layer efficiency}$$

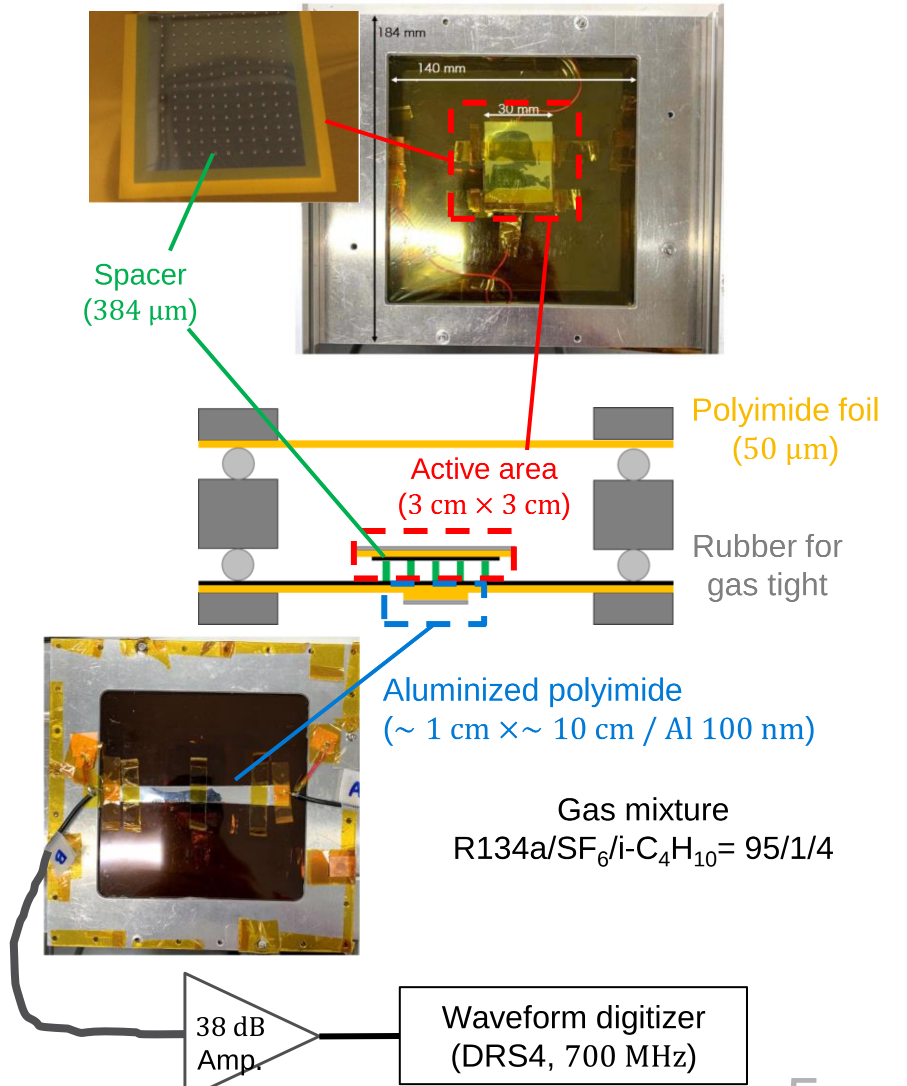
➡ $\epsilon_1 > 40\%$ **required** for $> 90\%$ efficiency

- **60% MIP efficiency** is achieved with single-layer RPC
- **90% MIP efficiency** is achievable with 4-layer RPC

Timing resolution

Achieved 160-170 ps

with 384 μm gap single-layer RPC

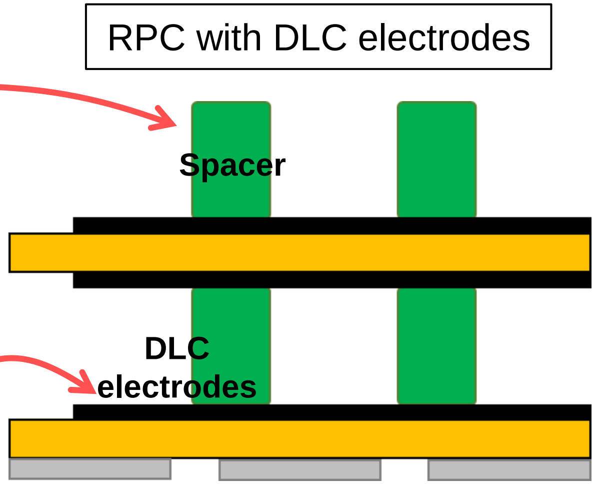


Today's talks

About manufacturing

➢**Pillar formation using new material**

- New design for obtaining wide gap spacing in RPC



➢Development of resistive electrode to achieve rate capability

- **Implement HV supply geometry → This talk**
- Control of DLC resistivity → Next talk

Problem of pillar formation

➢Pillar formation by photolithography technology

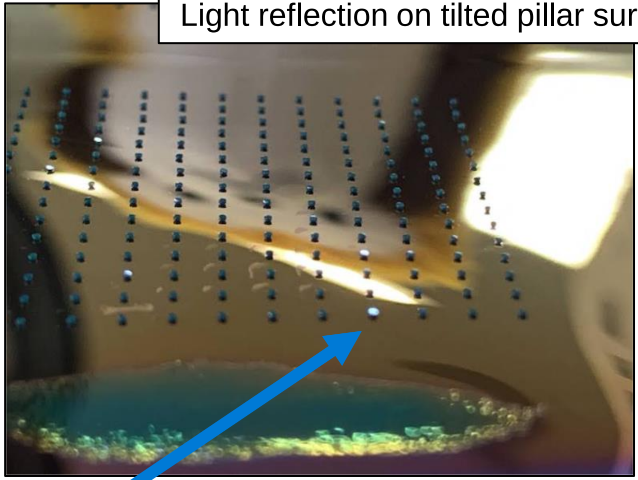
- The previous pillar material is **no longer available**
  ➡ **Use new pillar material**

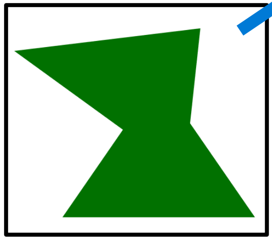
~~DuPont™ Pyralux®~~
➡ Solder resist

➢Pillar formation test

- 100 μm-thick on DLC
  - Done w/o any problem
- 300 μm-thick on Cu
  - Done w/ **non-flatness** of pillars
- 350 μm-thick on Cu
  - **Failed due to the difficulties reported**
    - Increased development time
      → Many pillars tilted or missing

Light reflection on tilted pillar surface



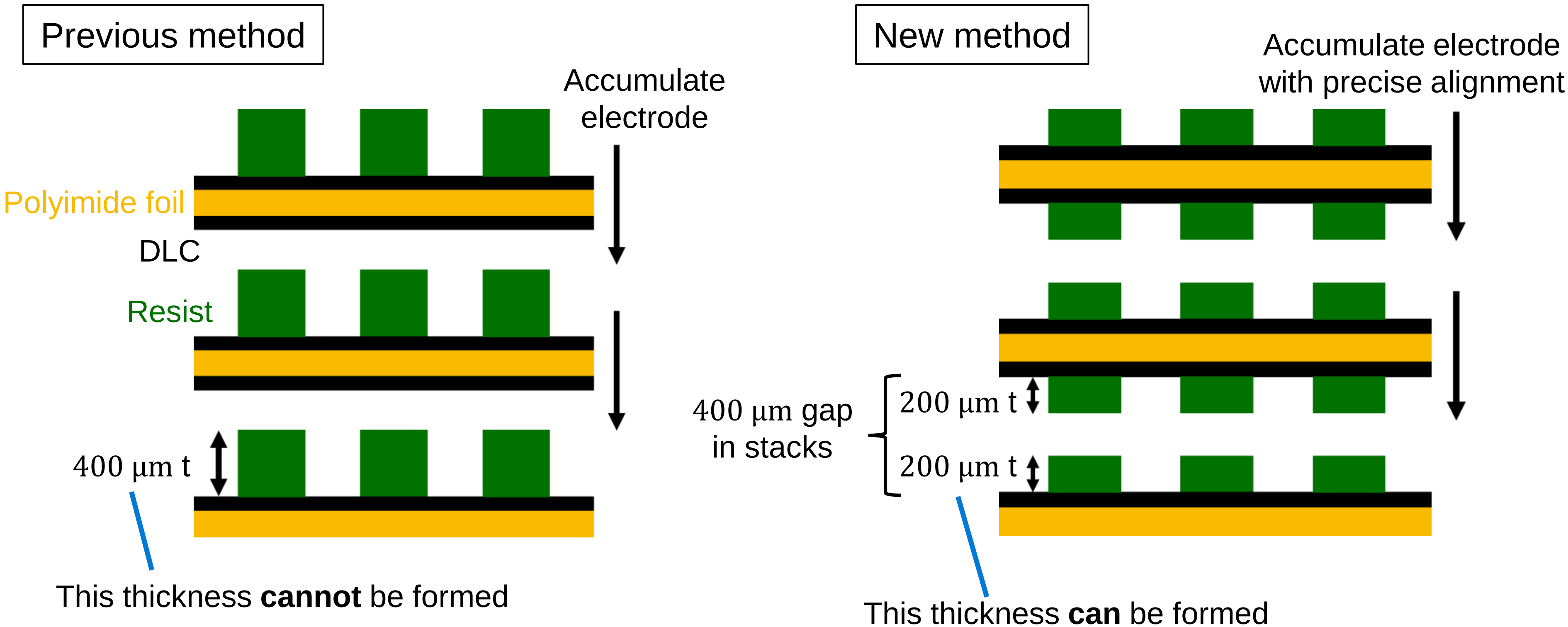


- Upper side: Inverse trapezoidal shape due to the amount of transmission during exposure
- Lower side: Photoresist remains due to insufficient development.

New strategy for obtaining sufficient gap

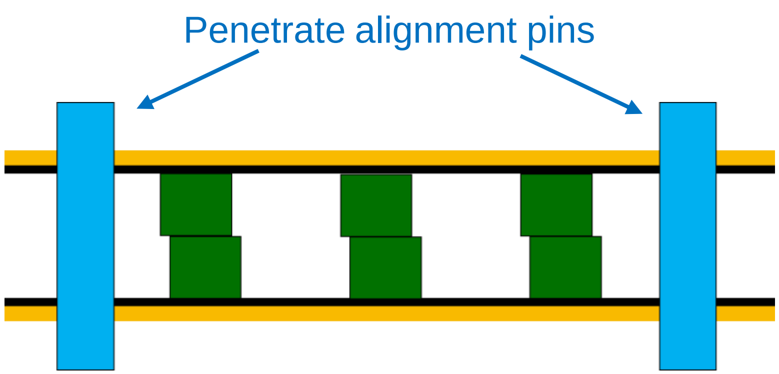
- ➢Formable up to 300 μm-thick
  - ➡ Not expected to have sufficient detection efficiency

- ➢**200 μm-thick pillars are attached on the both sides**



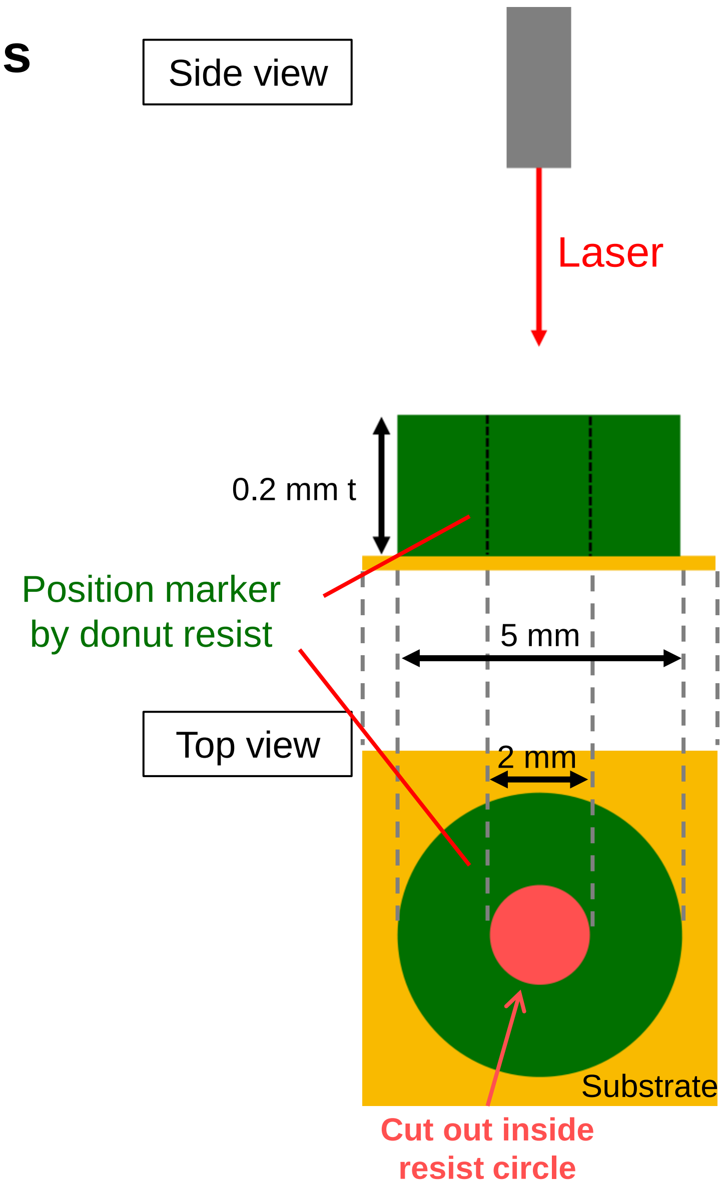
Alignment method

- **Alignment by alignment holes and pins**



- Alignment accuracy
  - Mask formation: ~ 1 μm (negligible)
  - Work by laser: < 50 μm (20 μm at best)
  - Alignment of both sides: < 50 μm

- Effect of misaligned pillars to be test
  - Electric field structure
  - RPC operations



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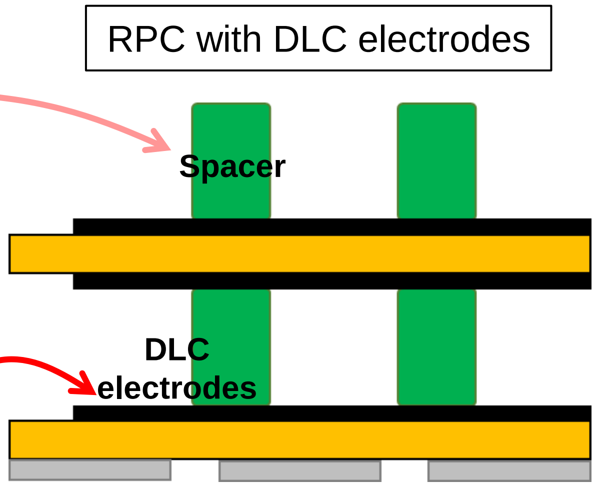
  - New design for obtaining wide gap spacing in RPC

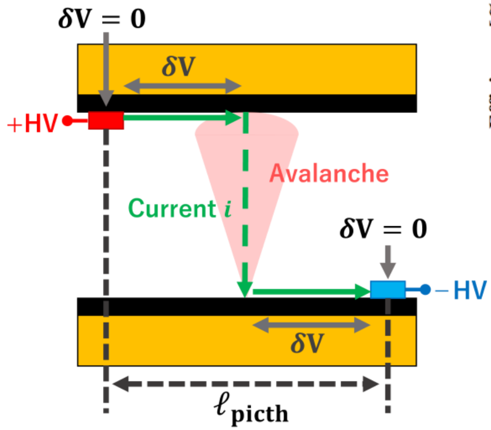


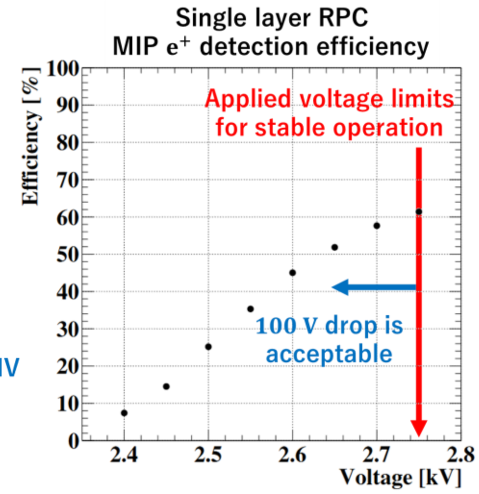
- **Development of resistive electrode to achieve rate capability**
  - **Implement HV supply geometry** → This talk
  - Control of DLC resistivity → Next talk

Rate capability

- Rate capability of RPC
  - **Determined by the voltage drop at DLC**

  ➡ **Up to $\delta V = 100$ V can be acceptable** from the voltage dependence of the detection efficiency

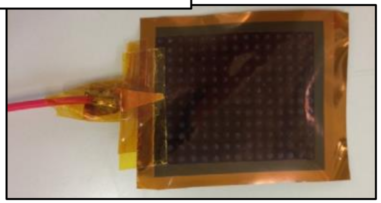


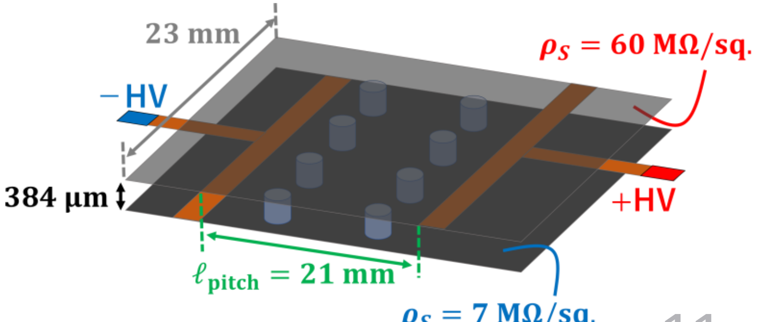


- Status of rate capability with $3\ \mathrm{cm} \times 3\ \mathrm{cm}$ prototype
  - **$1\ \mathrm{MHz/cm^2}$** (muon beams with $28\ \mathrm{MeV}/c$)
    - HV supply with Cu tape
    - Estimated $\delta V = 100\text{-}150$ V

  ➡ **Rate capability requirements will be achieved by improving electrodes to smaller voltage drop**

HV supply of prototype



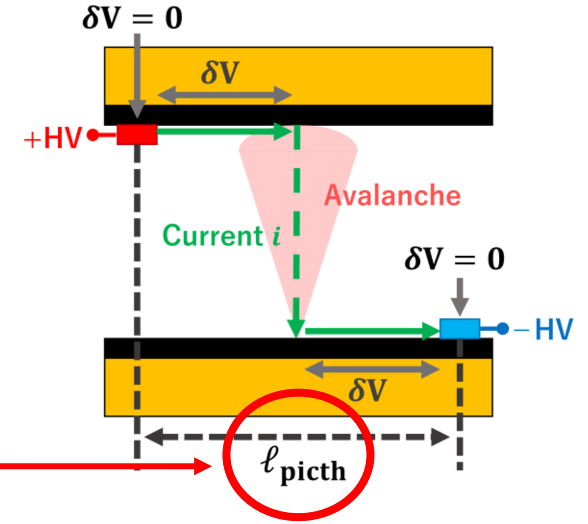


Suppression of voltage drop

- With DLC electrodes, voltage drop $\boldsymbol{\delta V}$ follows:

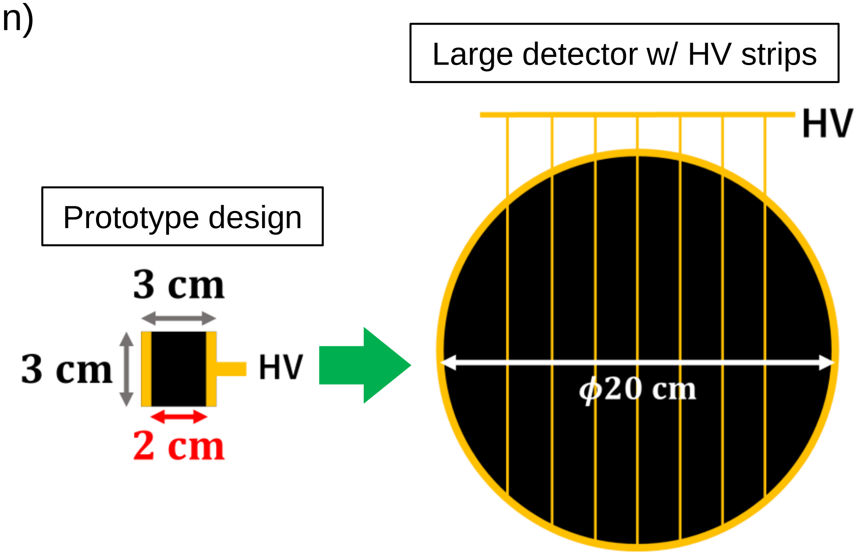
$$\nabla^2 \delta V(x,y) = \underbrace{Q_{\mathrm{mean}}(V_{\mathrm{eff}})}_{\text{Avalanche charge}} \cdot \underbrace{f(x,y)}_{\text{Hit rate}} \cdot \underbrace{\rho_S}_{\text{Surface resistivity}}$$

  - **Surface resistivity:** $\delta V \propto \rho_S$
  - **Boundary condition** of the equation
    ➡ Depends on geometry of HV supply: $\delta V \propto \ell_{\mathrm{pitch}}^2$



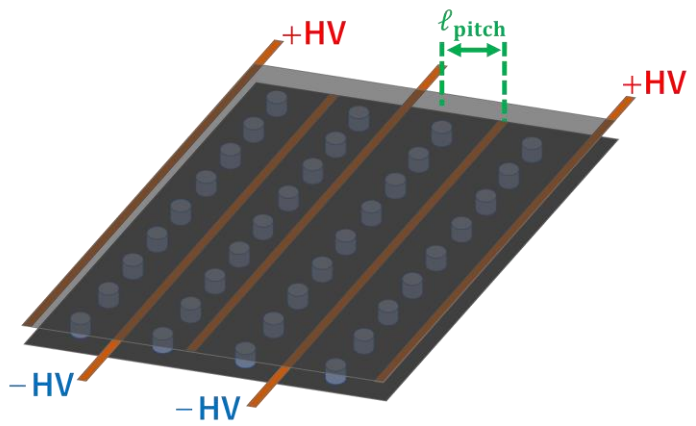
Larger δV with larger distance

- **HV supply geometry** (reported JPS2021-autumn)
  - The distance from HV supply must be small
    ➡ **strip geometry**
    - **In addition**,
      the strip geometry allows for larger detector



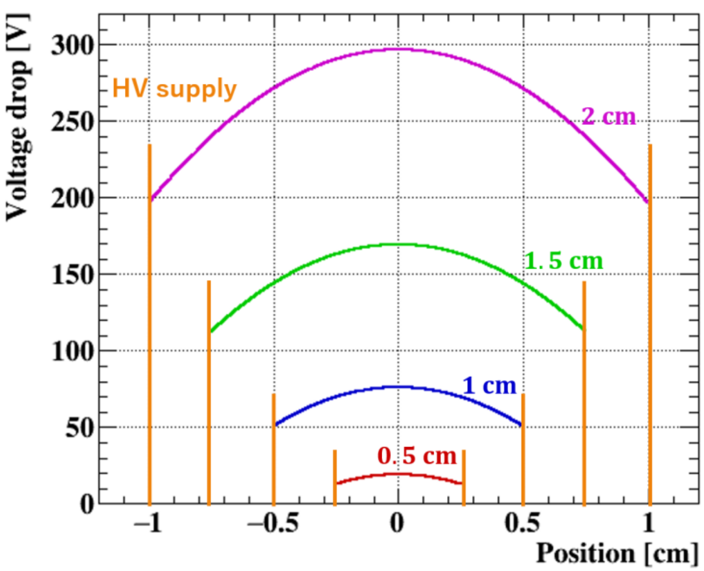
Determination of strip pitch

$$\nabla^2 \delta V(x,y) = \underbrace{Q_{mean}(V_{eff})}_{\text{Avalanche charge}} \cdot \underbrace{f(x,y)}_{\text{Hit rate}} \cdot \underbrace{\rho_S}_{\text{Surface resistivity}}$$



- Determination of strip pitch
  - $\ell_{pitch} < 2$ cm is required (from a study using prototype)
    - The strip becomes an inactive region
      ➡ Too narrow pitch is bad
  - δV dependency on ℓ_{pitch}
    - Calculated using the above equation
    - Optimal ℓ_{pitch} depends on surface resistivity

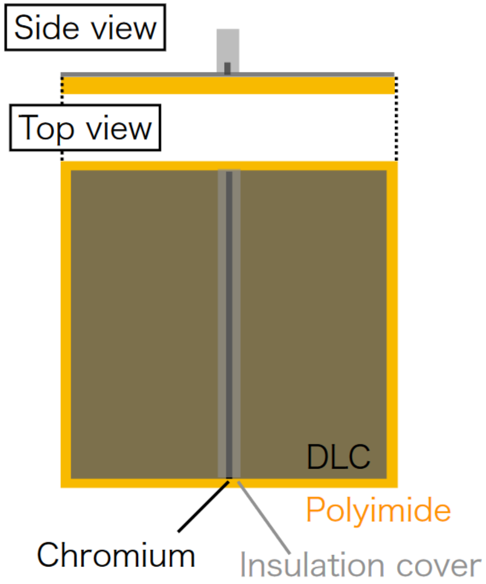
Voltage drop ($\rho_S = 10$ MΩ/sq)



In order to achieved $\delta V < 100$V,
$\ell_{pitch} = 1$ cm is required
➡ Implement conductive strips for HV supply

Implementation of HV supply

- Material for conductive strips
  - Use **chromium for conductive strips**
    - **Easy to bond to DLC**
    - Other metals are difficult to bond to DLC
  - The chrome strip is covered with an insulator
    ➡ **Prevention of discharge**



- Chromium sputtered on DLC (lift-off method)
  - Determination of strip width
    - **As thin as possible** to reduce inactive area
    - Masking and alignment accuracy
  ➡ **Inactive area: 2.1 %** for a detector with $\phi 20$ cm

	Conductive strips	Insulation cover
Material	Chromium	Dry resist
Thickness	100 nm	25 μm
Width	50 μm	200 μm

Prototype using the improved electrode is now in production

Summary and prospect

- High-rate capable RPC with DLC electrodes is under development for MEG II upstream RDC

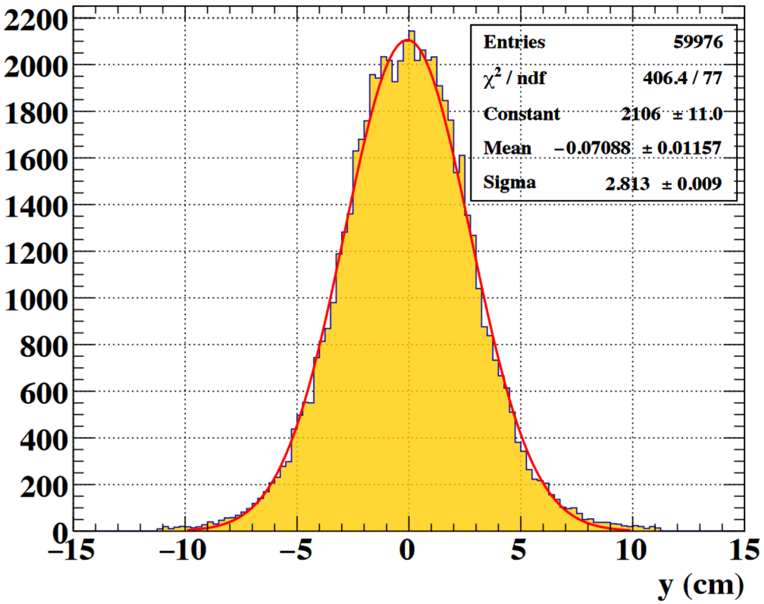
- Development of a new pillar structure
  - 0.2 mm-thick pillars are attached on the both sides
  - Electrodes are accumulated with precise alignment

- Development of electrodes for improving rate capability
  - Implementation of conductive strips for HV supply
    - Use chromium as conductive strips and protected by insulating cover
  - Prototype is now in production

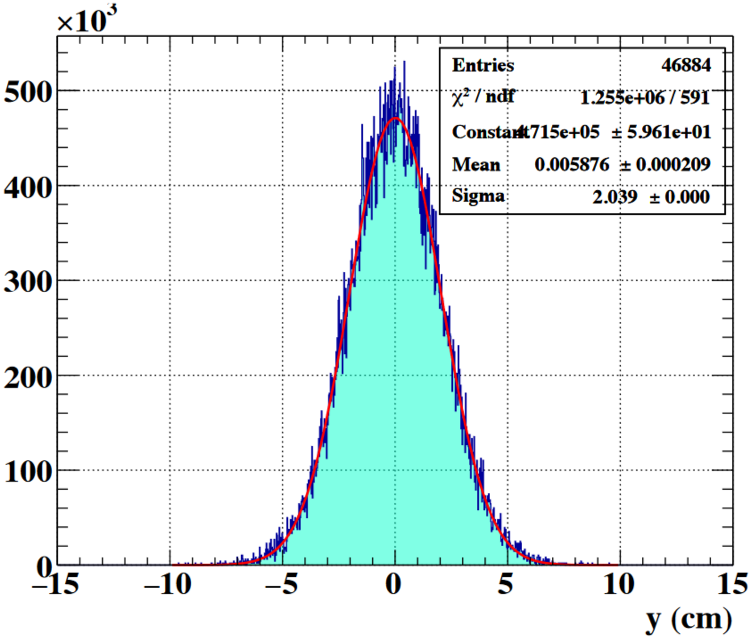
- Planned studies
  - Rate capability test using improved electrodes in this year
    ➡ If performance can be demonstrated with a prototype, the requirements can be achieved with a large detector

Backups

RMD e^+ distribution



RMD e^+ ($E_\gamma > 48$ MeV)
$\sigma = 2.8$ cm



μ beam profile
$\sigma = 2.0$ cm

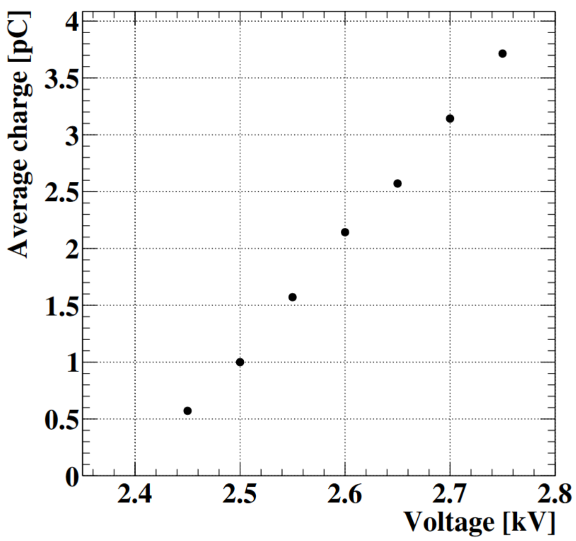
Status of rate capability studies

$$\nabla^2 \delta V(x,y) = Q_{\text{mean}}(V_{\text{eff}}) \cdot f(x,y) \cdot \rho_S$$

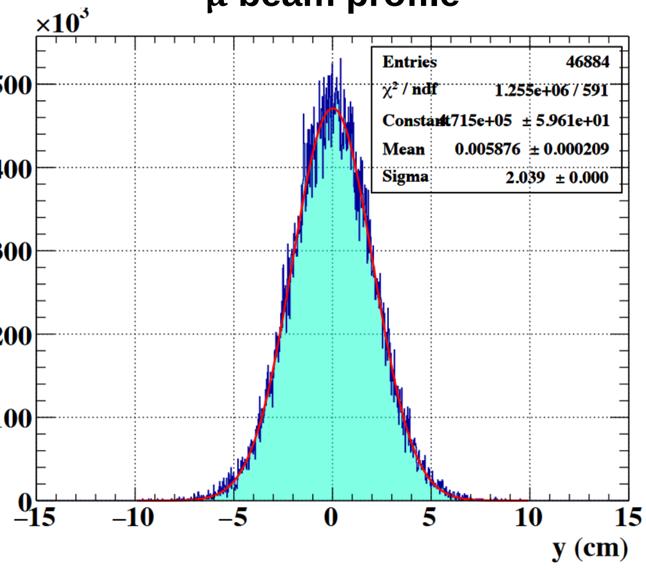
Avalanche charge — Hit rate — Surface resistivity

- Known parameters (reported in JPS2021-autumn)
  - **Requirements to δV: $< 100\ \mathrm{V}$**
    → Determined by the voltage achieved $> 50\%$ with single-layer
  - **Avalanche charge:** measured for low-momentum muon beam
  - **Hit rate: $4\ \mathrm{MHz/cm^2}$** at the center

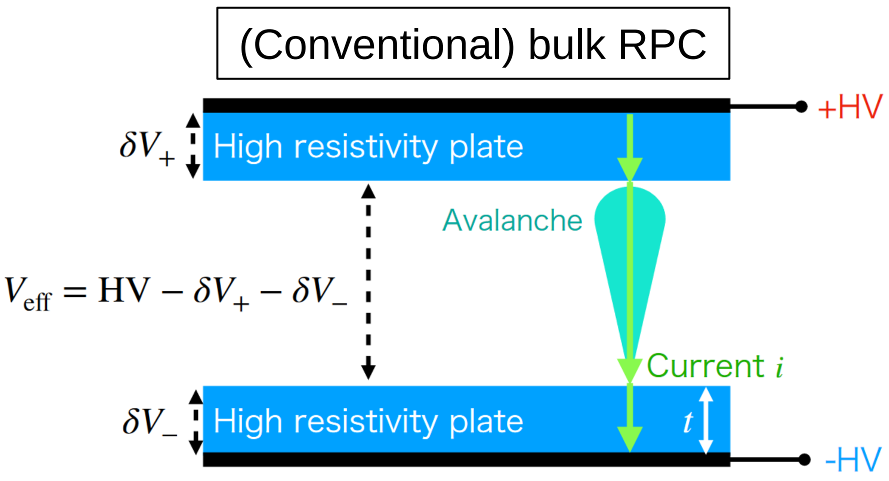
Average charge of avalanche

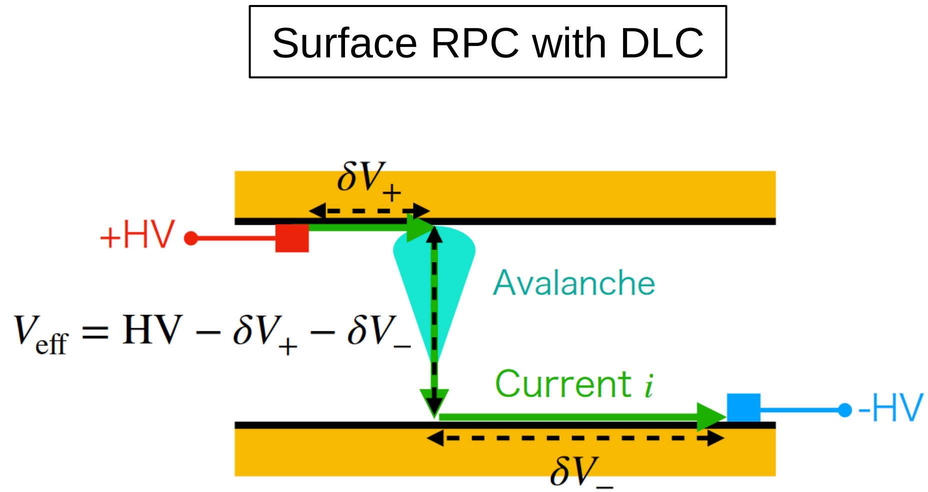


μ beam profile



Voltage drop of RPC





$$\delta \mathrm{V} = Q_{\mathrm{mean}}(\mathrm{V}_{\mathrm{eff}}) \cdot f(x, y) \cdot \rho_V \cdot t$$

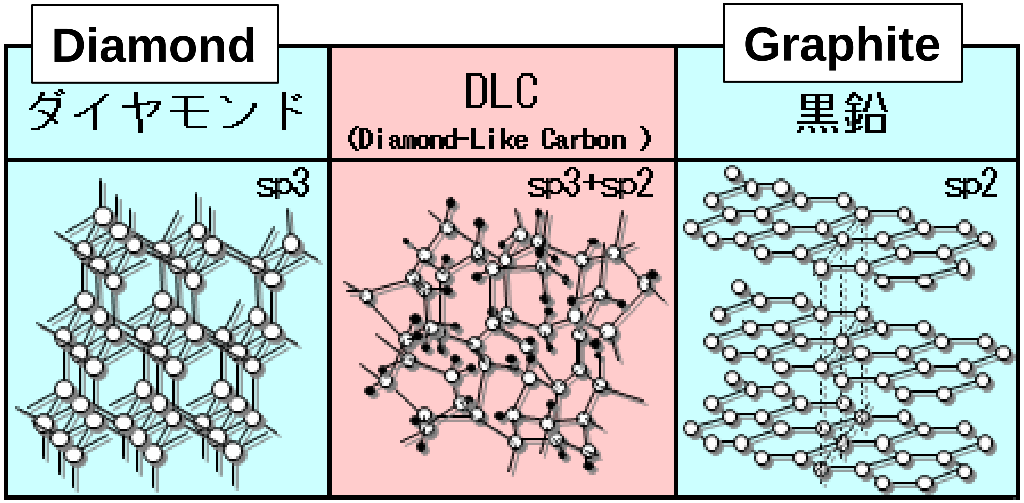
$$\nabla^2 \delta \mathrm{V} = Q_{\mathrm{mean}}(\mathrm{V}_{\mathrm{eff}}) \cdot f(x, y) \cdot \rho_S$$

- The voltage drop due to high current on resistive electrodes
  - Current paths are different between conventional and surface type
  - ➡ In surface RPC, the distance between conductors affects voltage drop

Diamond-Like Carbon (DLC)

- Amorphous structure with graphite (sp^2) and diamond (sp^3) bonds
  - sp^2: Electrically conductivity
  - sp^3: Insulating properties

- Features:
  - **High-definition patterning** ($< 10\ \mu\mathrm{m}$)
  - **Wide range of surface resistivity** can be set ($50\ \mathrm{k} - 3\ \mathrm{G}\Omega/\mathrm{sq}$)
    - Film thickness adjustment
    - Nitrogen doping
  - **High adhesion** to polyimide
  - **Chemically stable**

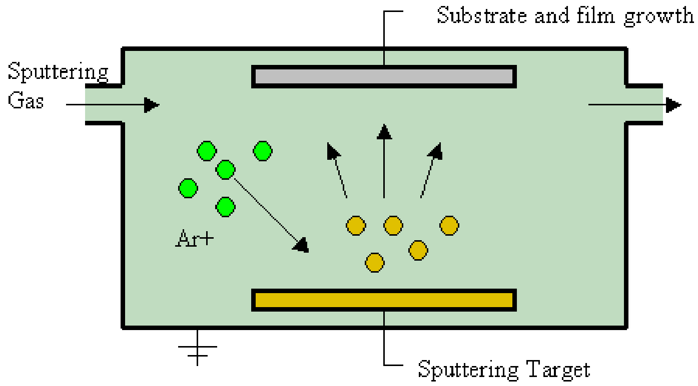


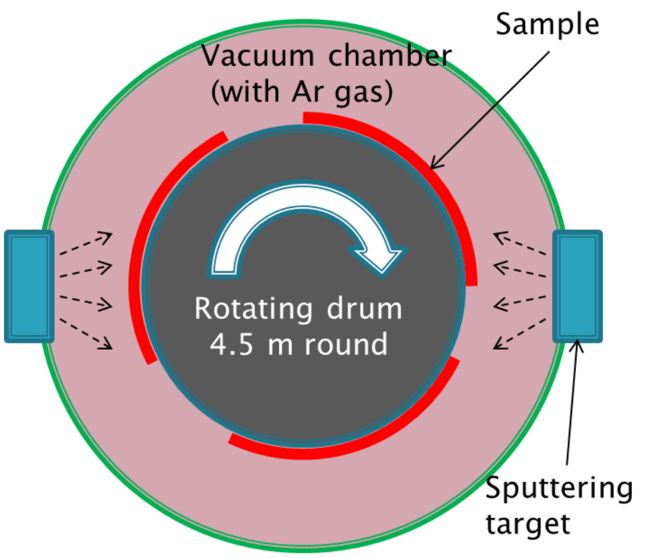
Comparison of diamond, DLC and graphite structures
Ref) https://nippon-itf.co.jp/technical/article/about-dlc.html

Sputtering technology

➢Sputtering Method

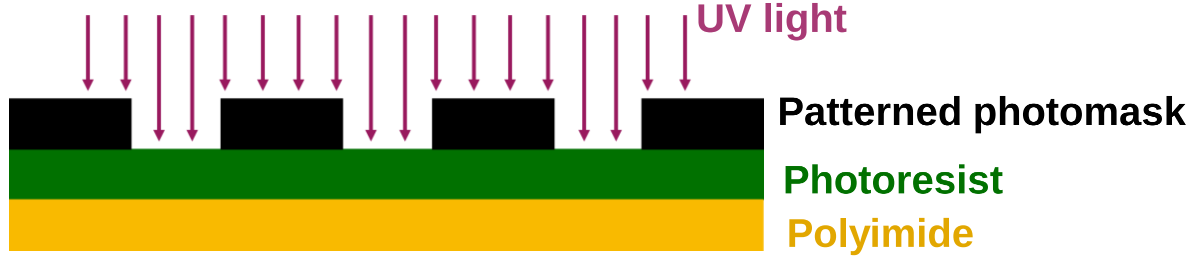
1. Inert gas (mainly Ar) is added in a vacuum
2. Apply a negative charge to the deposition material
   ➡ Ionizes gas atoms by causing glow discharge
3. Gas ions collide with target at high velocity
4. The beaten-up target constituent particles adhere to and deposit on substrate surface
   ➡ Thin film formation





Pillar formation using photoresist

1. Masked and exposed with UV light



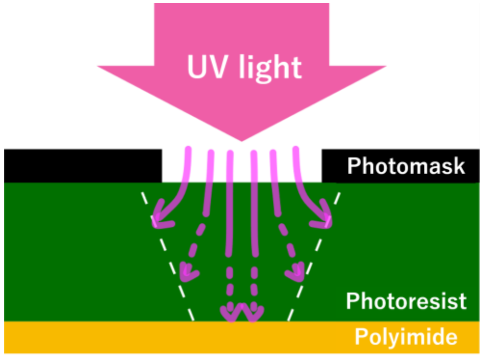
2. Dissolve non-exposed areas with developer

3. Pillar is completed

4. Heat harden (Baking)

Pillar formation

- Inverse trapezoidal shape
  due to the amount of transmission during exposure



- Photoresist remains due to insufficient development