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

–~~検出器の性能評価~~–
高抵抗電極の抵抗率コントロール

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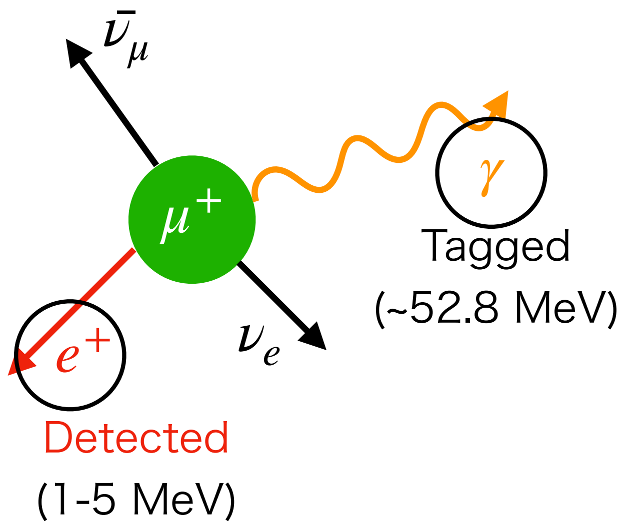
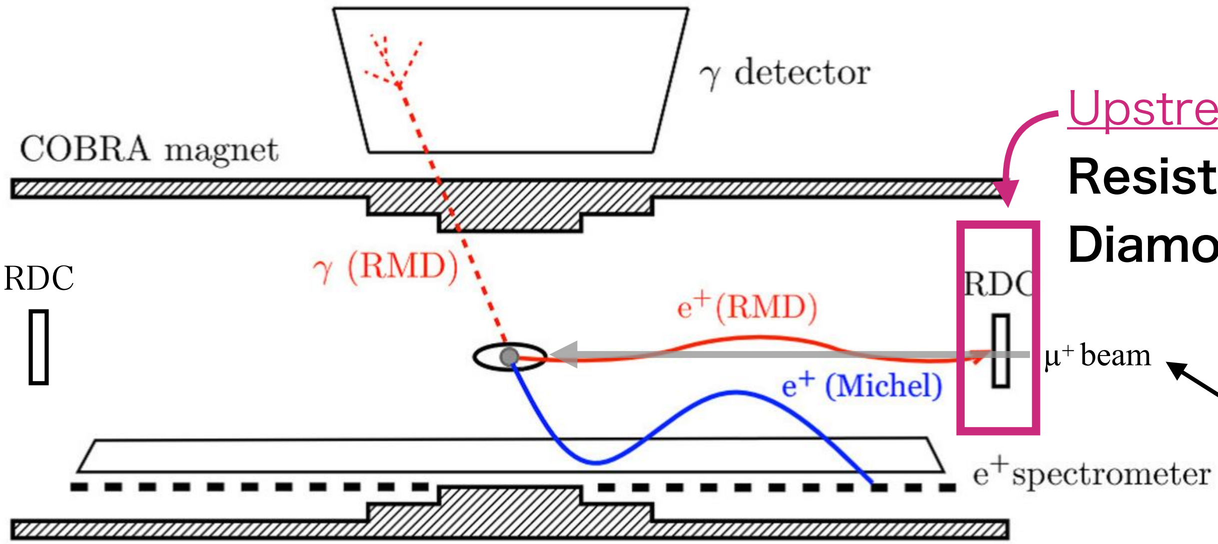
Outline

- Introduction
  - Upstream RDC for MEG II
  - RPC rate capability
- Precise control of DLC resistivity
  - Requirements to resistivity
  - Sputtering thickness
  - Thermal annealing
- Summary & prospects

MEG II and RDC

- MEG II searches for $\mu \to e\gamma$ decay
- RDCs are detectors to tag BG-γ from Radiative Muon Decay (RMD)





Upstream RDC candidate:

Resistive Plate Chamber (RPC) with Diamond-Like Carbon (DLC) electrodes

The μ^+ beam

- Low momentum ($28\ \mathrm{MeV}/c$)
- **High rate (1×10^8 /s)**

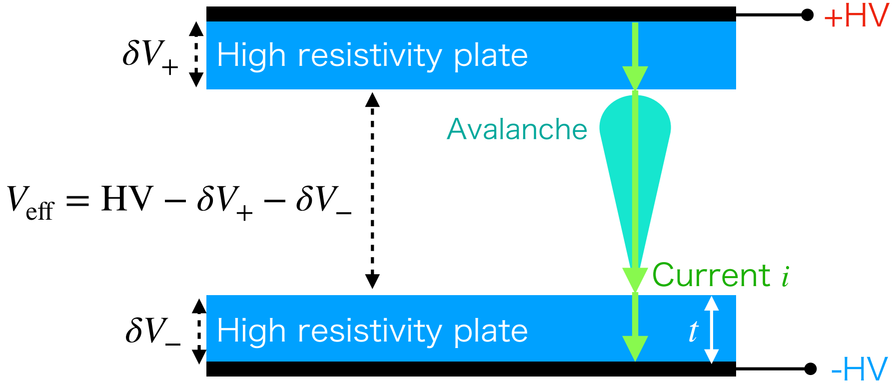
Rate capability

- Large current on resistive electrodes at high rate

➡ Voltage drop δV reduces effective applied HV V_{eff}

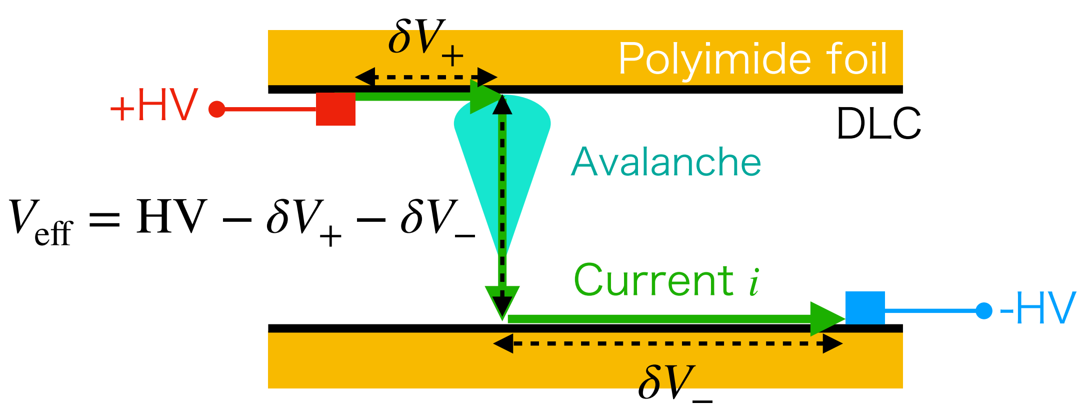
➡ Gas gain reduction

(Conventional) bulk RPC



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

Surface RPC



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

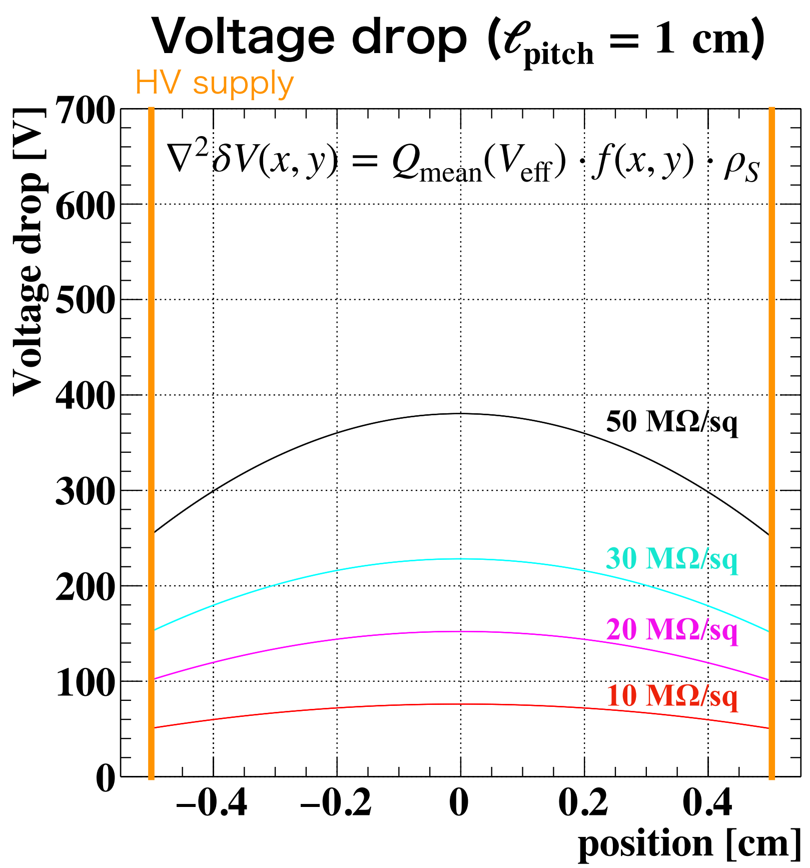
Focus on surface resistivity of DLC in this talk

Requirements to resistivity

- Resistivity is
  - Too low: unstable operation due to discharge
  - Too high: less rate capability

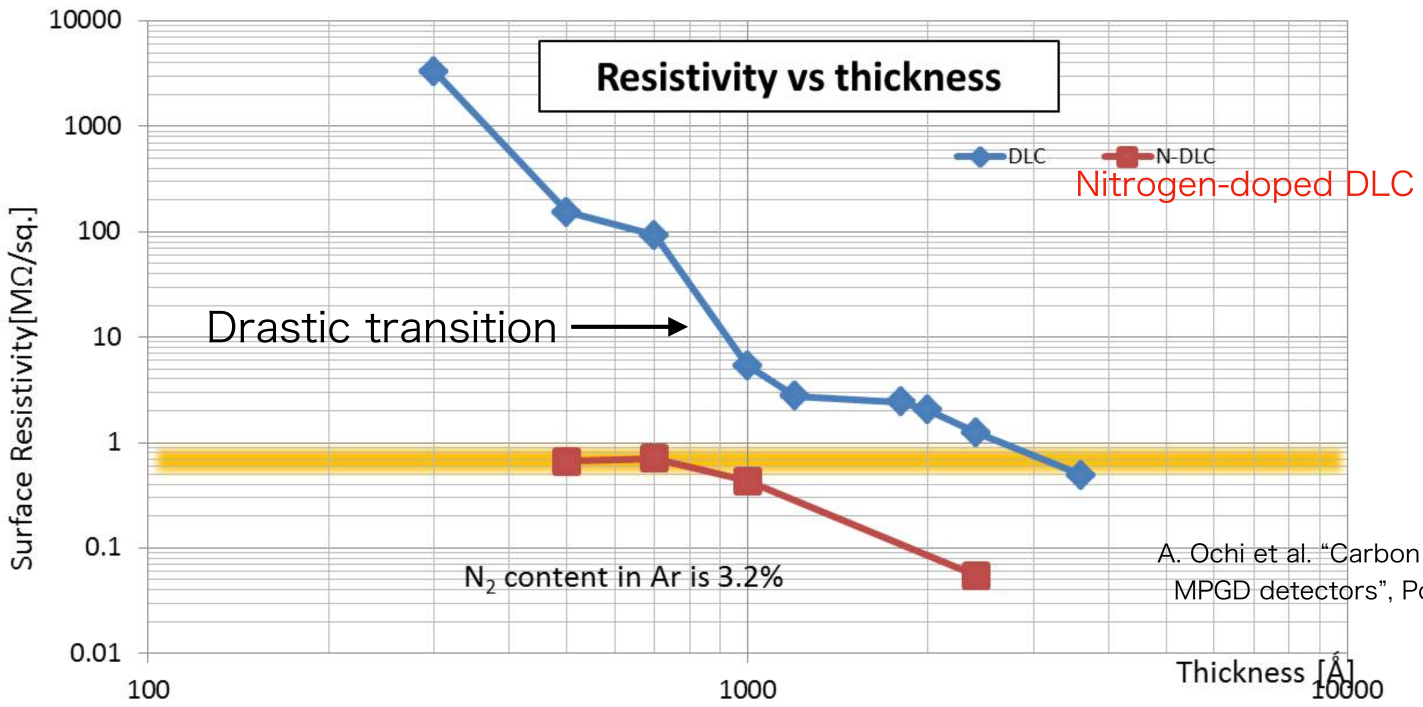
- Stability study
  - 1 MΩ/sq: Unstable
  - >20-30 MΩ/sq: Stable
  - (Reported in JPS autumn 2021)

- **Production with ρ_S = 10 MΩ/sq**
  - Sputtering thickness
  - Thermal annealing
- **Operation test at ρ_S = 10 MΩ/sq**



Sputtering thickness

- Rough adjustment by sputtering thickness
  - Up to factor 10 difference b/w ordered and produced
  - Factor 2 difference by resistivity measurement during the sputtering



A. Ochi et al. “Carbon sputtering technology for MPGD detectors”, PoS TIPP2014 (2014) 351

Thermal annealing

- DLC resistivity is reduced permanently after heating

➡ Thermal annealing to adjust the resistivity precisely
  - Temperature dependence
  - No heating time dependence (if >10 min)
- Measure surface resistivity before/after heating
  - Heat temperature: 100-210˚C
  - Heating time: 60 min

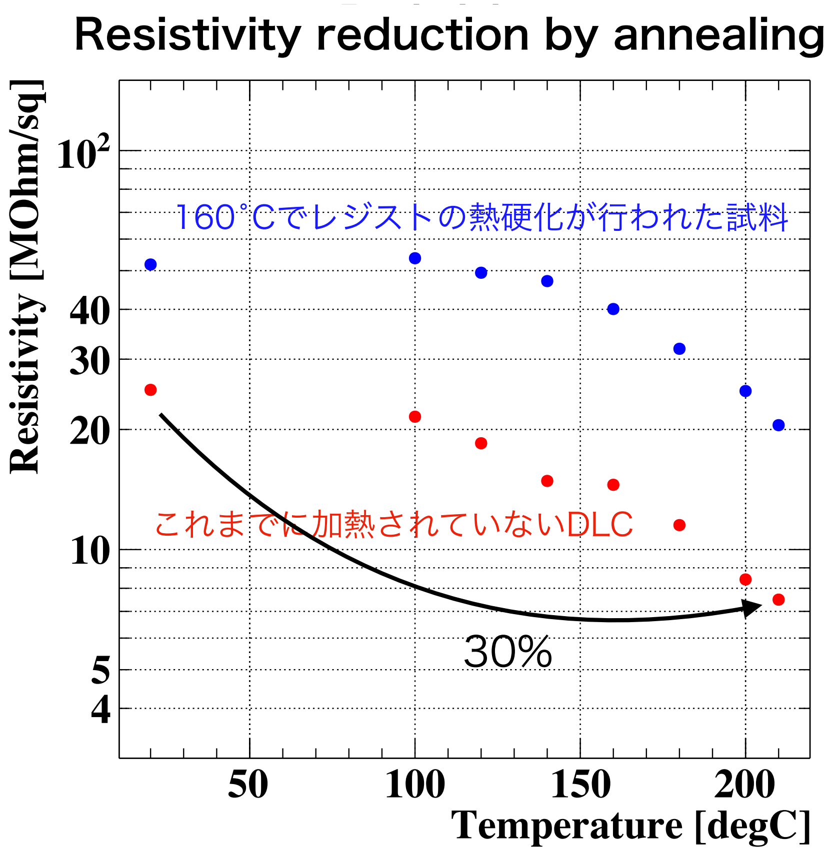
3 cm size DLC samples

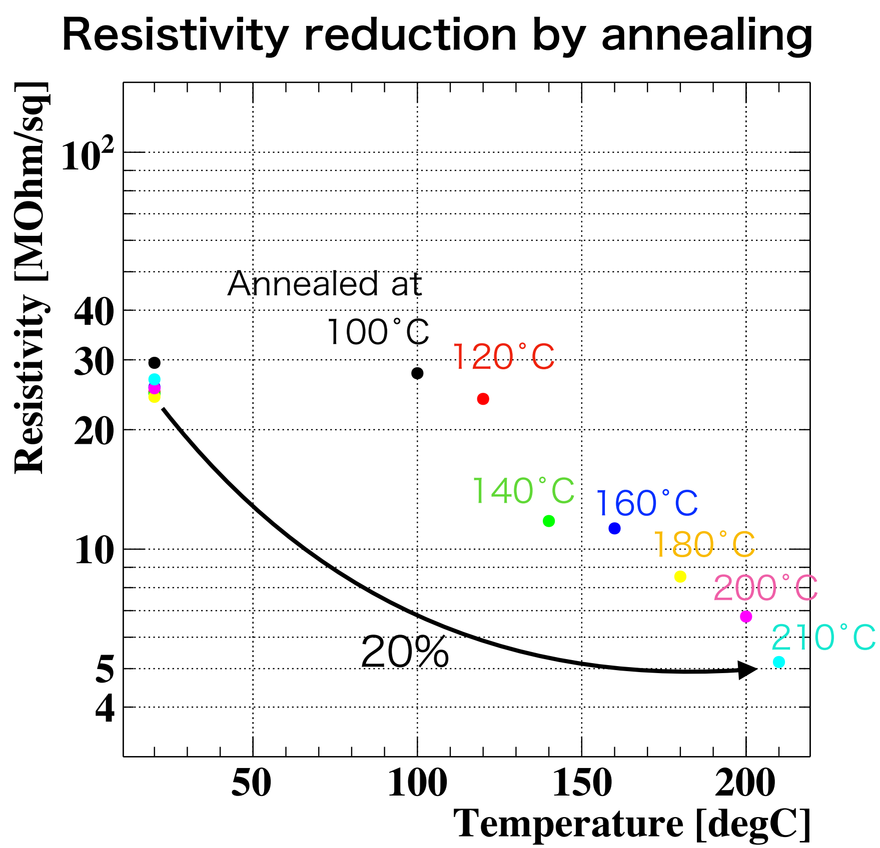
Oven to heat

Samples to be heated

Thermal annealing

- Heating pattern
  - Room temp. → 100˚C → Room temp. → 120˚C → ···
  - Room temp. → heating temp. (100˚C, 120˚C, ···)
- **Resistivity can be adjusted with <15% precision**
  - Measurement uncertainty: 15%

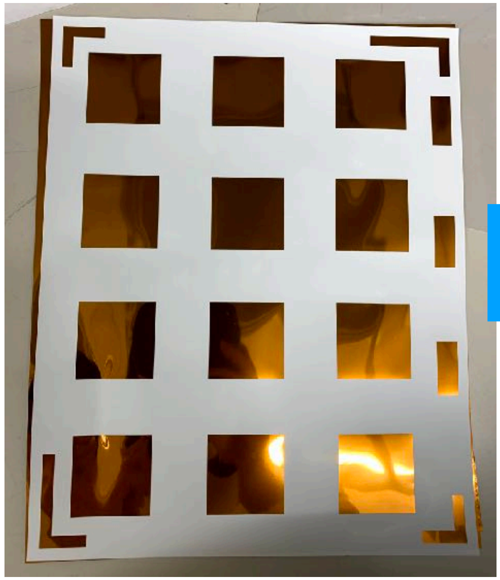




Electrode production process

- DLC is heated on the way to harden photo-resist
  - Bake at 150˚C
  - 40-50% resistivity reduction
- The baking must be considered for final resistivity adjusted

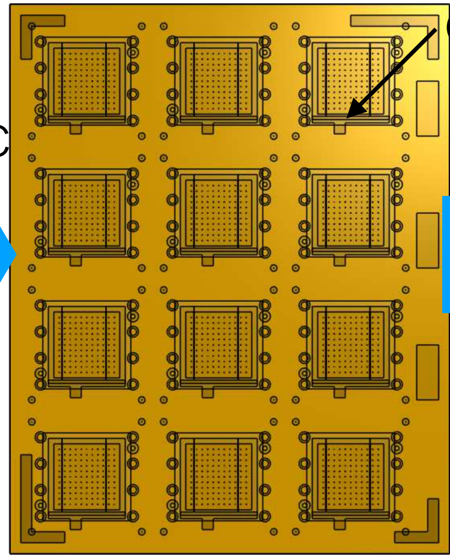
Aluminised PI with mask



Aluminised PI with DLC

Heat
@150˚C

Finished electrode (image)



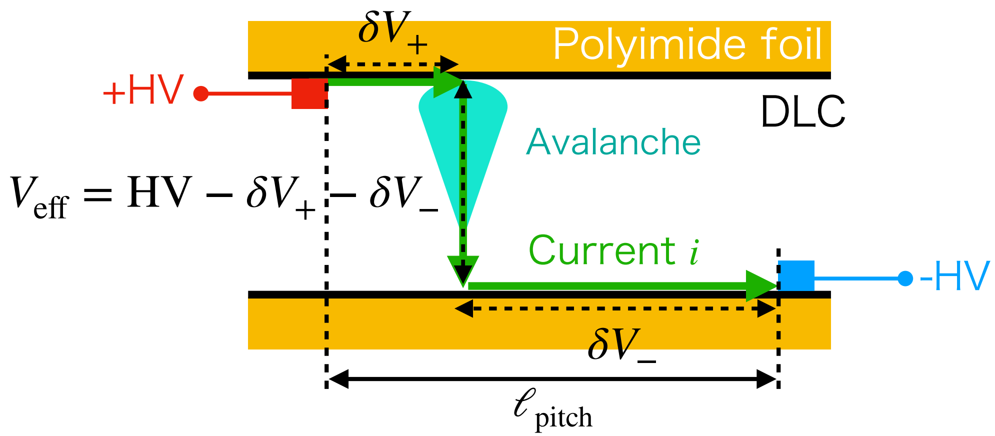
Cr + photo-resist

(If necessary) Annealing

10 MΩ/sq achievable

Possible options of parameters

- Voltage drop δV
  - ℓ_{pitch} dependence: $\delta V \propto \ell_{\mathrm{pitch}}^2$
  - ρ_S dependence: $\delta V \propto \rho_S$



- **Current optimal option**
  - **ℓ_{pitch} = 1 cm, ρ_S = 10 MΩ/sq → δV ~ 80 V**

- If unstable operation with ρ_S = 10 MΩ/sq,
  - ρ_S = 20 MΩ/sq, ℓ_{pitch} = 8 mm → δV ~ 100 V
    - (Dead region increases by 0.5%)
  - Further optimisation needed

Summary

- RPC with DLC electrodes is under development for background reduction in the MEG II experiment

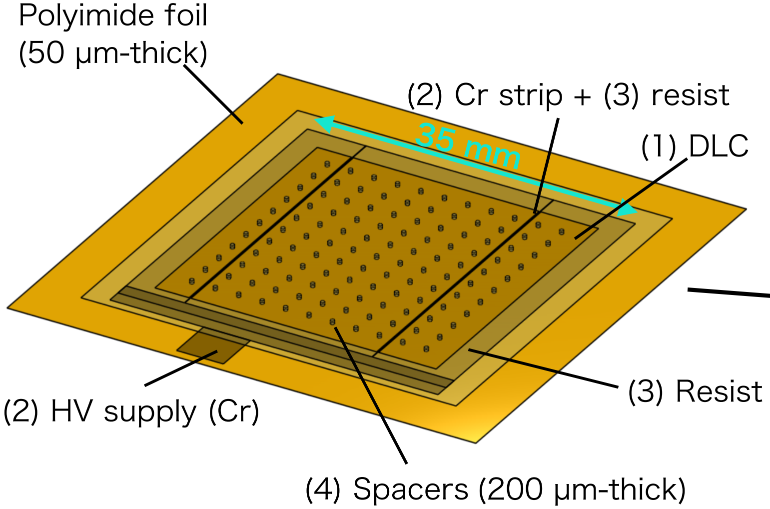
- DLC surface resistivity of electrode must be controlled to 10 MΩ/sq
  - Too low: unstable operation (1 MΩ/sq)
  - Too high: less rate capability (20-30 MΩ/sq)

- Ways to adjust the resistivity
  - Sputtering thickness adjustment (rough by factor 2)
  - Thermal annealing (<15% precision)

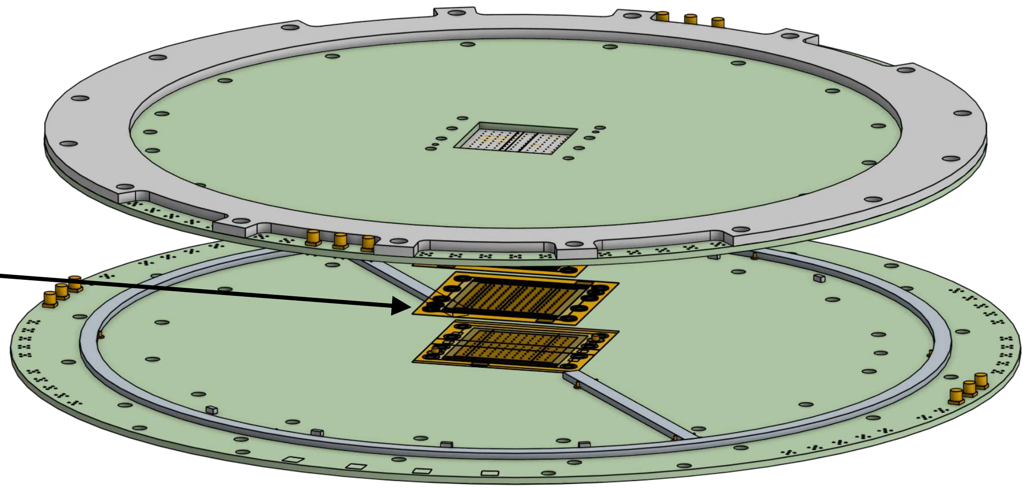
Prospects

- Operation test with ρ_S = 10 MΩ/sq
- Improved prototype detector is in production
  - Improved electrode is in production
  - Evaluate its performance using β ray and μ beam at PSI
- Aim to install in 2023 physics run
  - Sensitivity improvement estimated by ~10%

Improved electrode



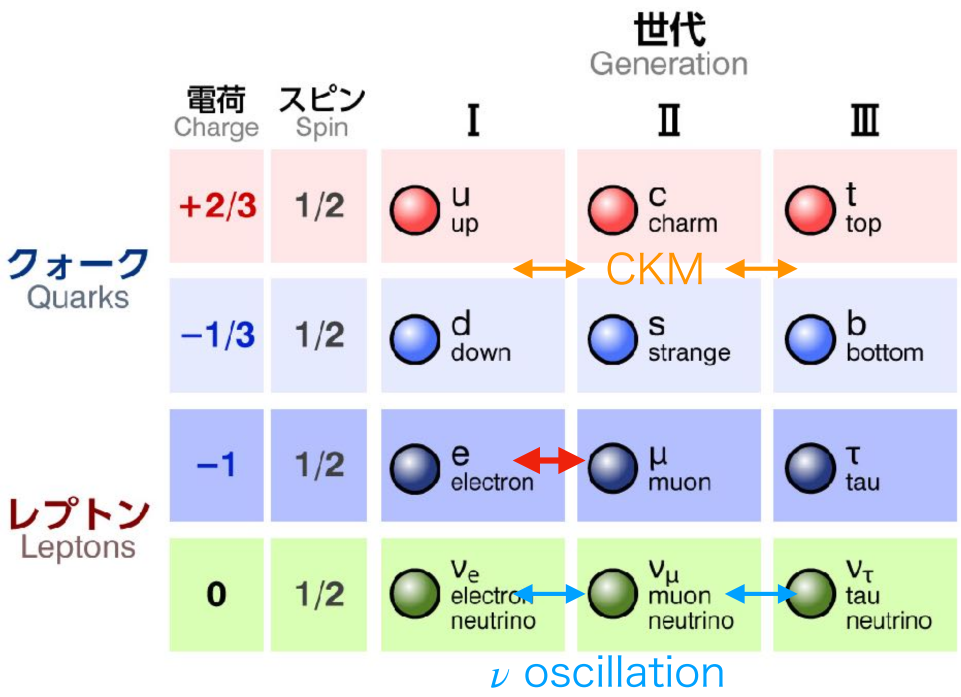
Improved prototype detector

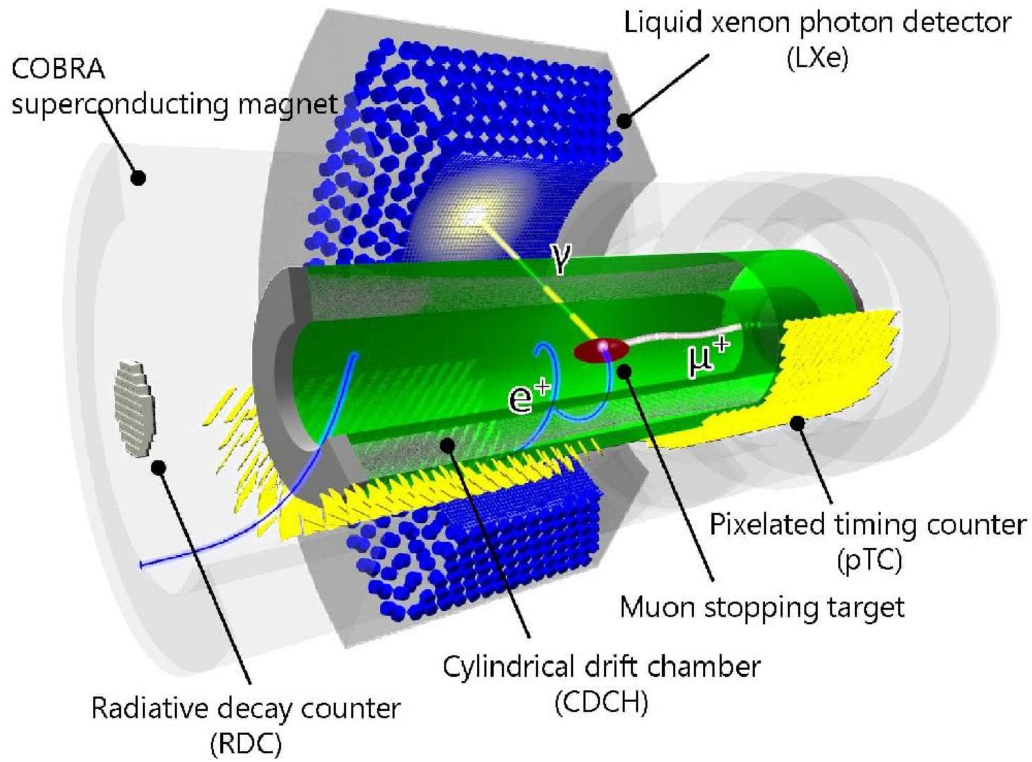


Backup

MEG II experiment

- MEG II searches for $\mu^+ \to e^+\gamma$ decay with the sensitivity of 6×10^{-14}
  - SM + ν osc: $\mathscr{B}(\mu^+ \to e^+\gamma) \sim 10^{-54}$
  - BSM (SUSY-GUT, SUSY-seesaw): $\mathscr{B}(\mu^+ \to e^+\gamma) \sim 10^{-11} - 10^{-15}$

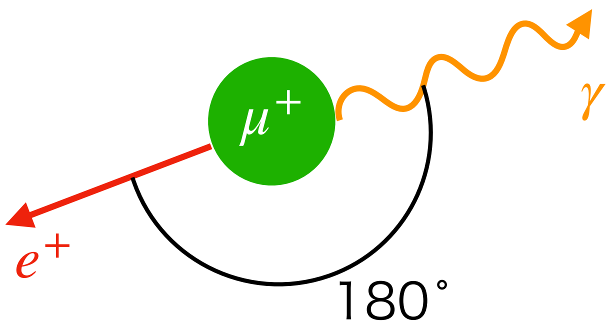




MEG II signal and background

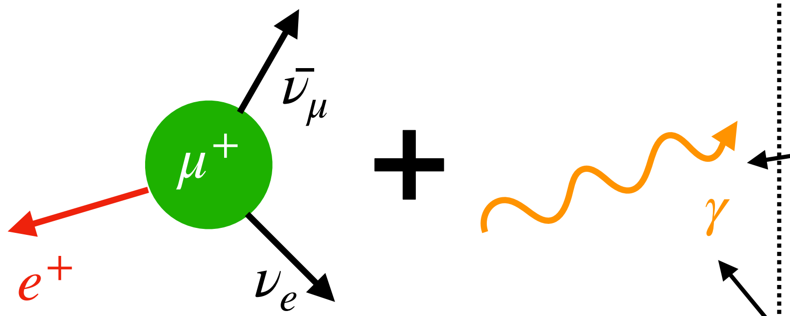
- MEG II searches for $\mu \to e\gamma$ decay, one of charged lepton flavour violation (cLFV) channels
- Dominant background is accidental coincidence of BG-e^+ and BG-γ

Signal



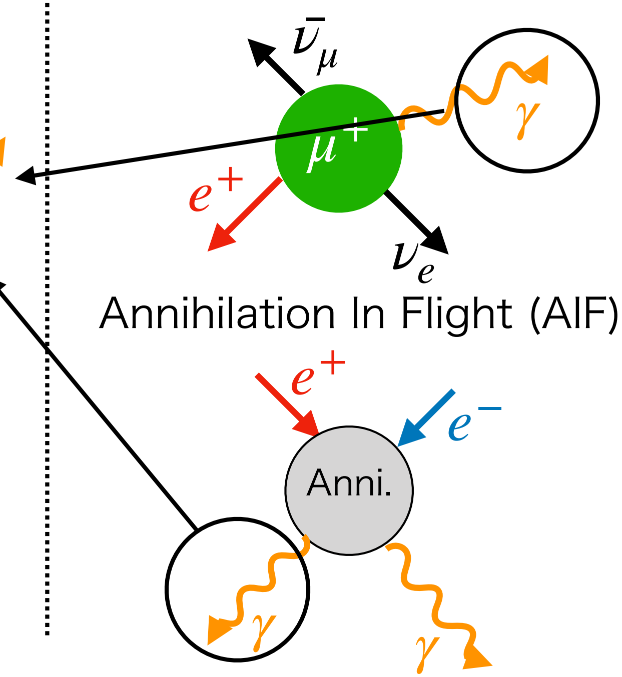
- The same energy of 52.8 MeV
- Opposite direction
- The same timing

Accidental BG



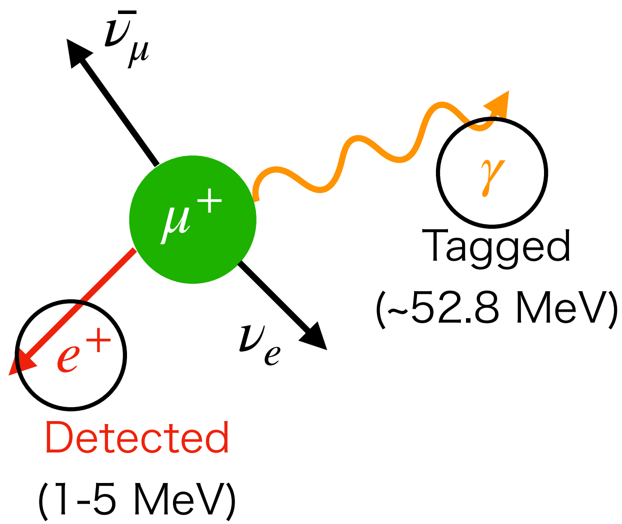
Signal-like accidental coincidence of e^+ and γ with ~52.8 MeV

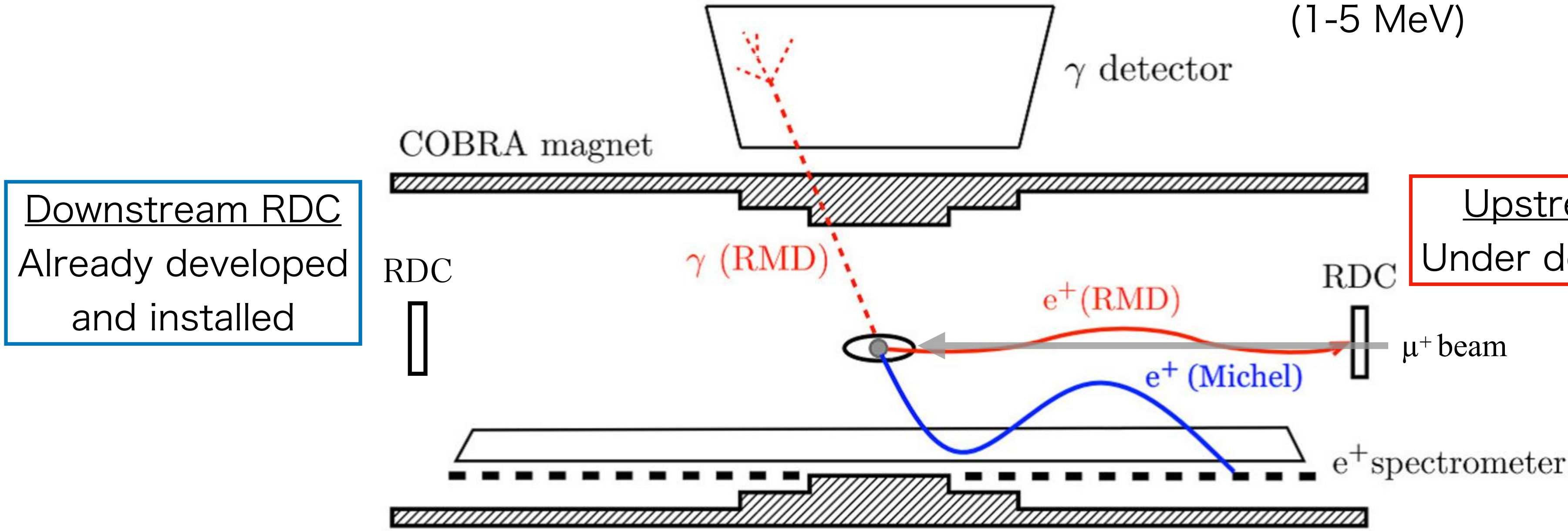
Radiative Muon Decay (**RMD**)



Radiative Decay Counter

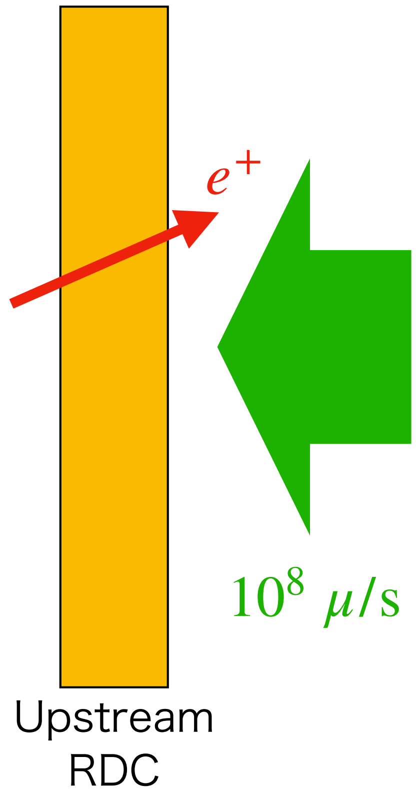
- Radiative Decay Counter (RDC) detects RMD e^{+} with 1-5 MeV to tag BG-γ
- RDCs will be installed at both upstream and downstream of target
- Upstream RDC is under development





Requirements for upstream RDC

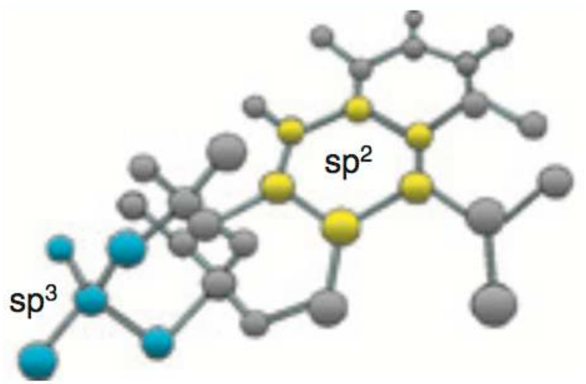
1. <0.1% X_0 material budget
   - μ beam with 21 MeV/c must pass through the detector
2. Rate capability for $10^8\ \mu/\mathrm{s}$ ($4\ \mathrm{MHz/cm^2}$)
3. Radiation hardness for >60 weeks operation
4. 90% efficiency for RMD e^+ with 1-5 MeV
5. 1 ns timing resolution
6. 20-cm diameter detector size



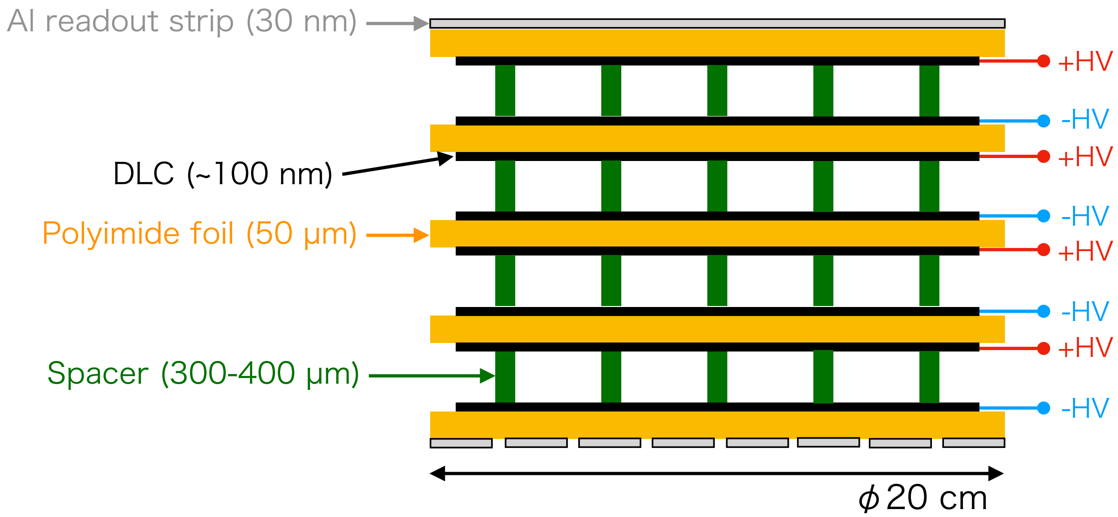
High-rate capable RPC with Diamond-Like Carbon electrodes for upstream RDC

RPC with DLC technology

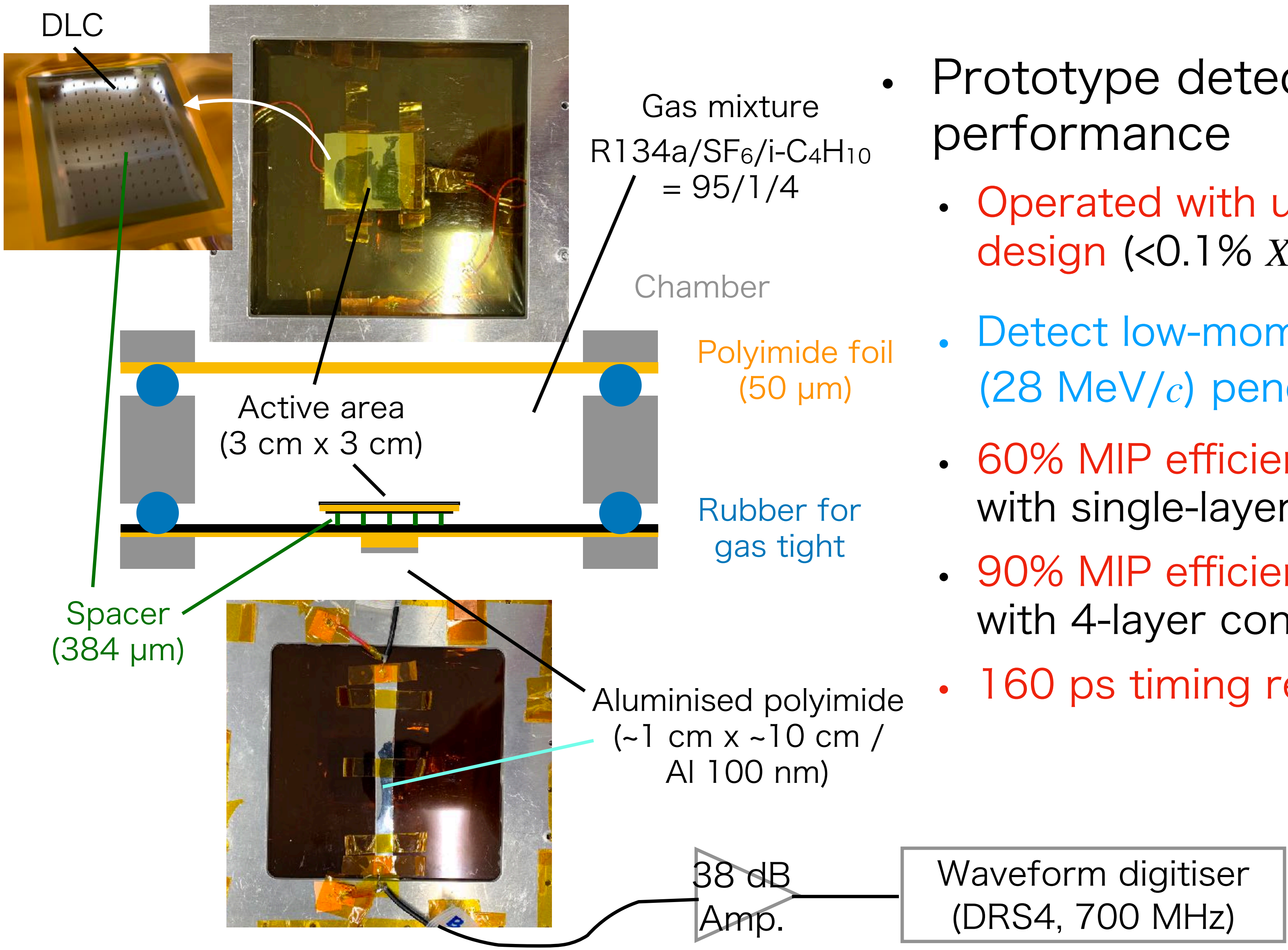
- Diamond-Like Carbon (DLC) is used as resistive electrodes
  - DLC is sputtered on 50-μm-thick polyimide foil
  - ➡ Small material budget can be achieved
  - DLC resistivity is adjustable
  - ➡ Small resistivity can be achieved, which is important rate capability



- MEG II RPC design
  - 4 layers ← Higher efficiency
    - $\epsilon_n = 1 - (1 - \epsilon_1)^n$
  - <0.1% X_0 material budget
    - 50 μm Polyimide foil → 0.018% X_0
    - 30 nm aluminium → 0.0034% X_0



RPC prototype detector



- Prototype detector performance
  - Operated with ultra-low mass design (<0.1% X_0)
  - Detect low-momentum μ^+ (28 MeV/c) penetrating detector
  - 60% MIP efficiency is achieved with single-layer configuration
  - 90% MIP efficiency is achievable with 4-layer configuration
  - 160 ps timing resolution

Voltage drop

Boundary condition determined

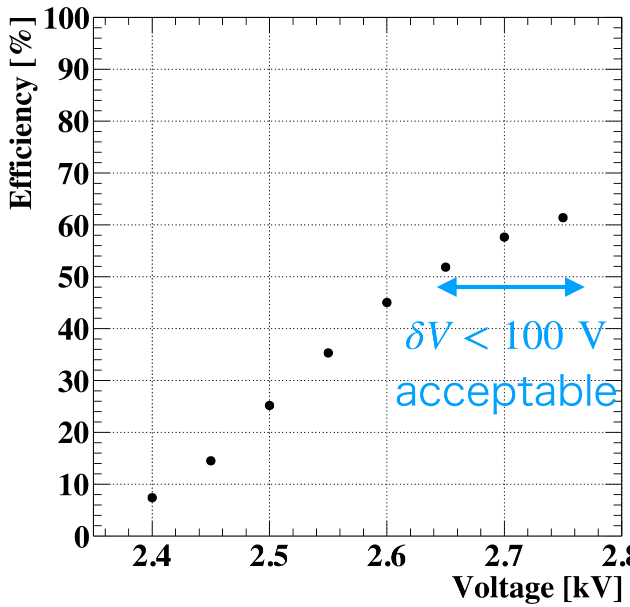
$$\nabla^2 \delta V(x,y) = Q_{\mathrm{mean}}(V_{\mathrm{eff}}) \cdot f(x,y) \cdot \rho_S$$

Acceptable voltage drop

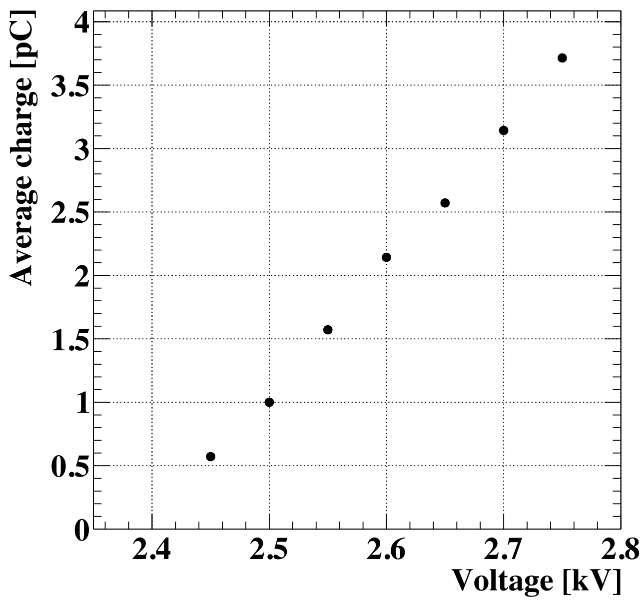
Average charge

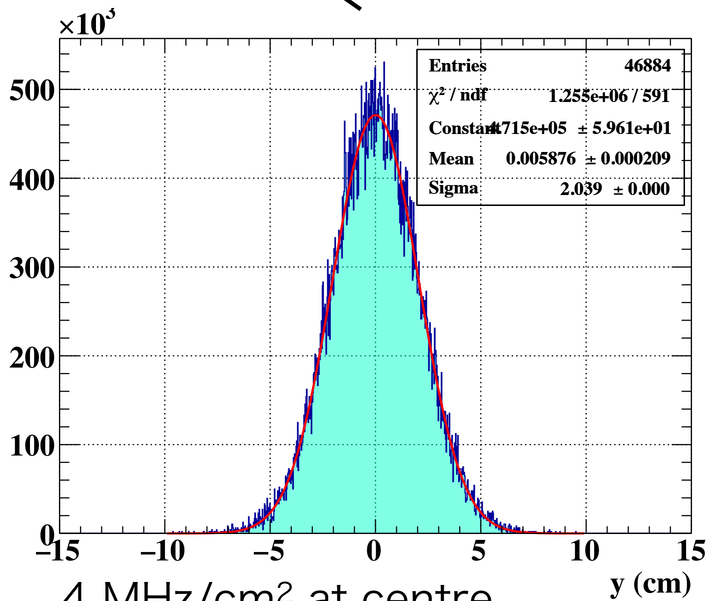
μ beam profile

Efficiency vs voltage



Average charge vs voltage

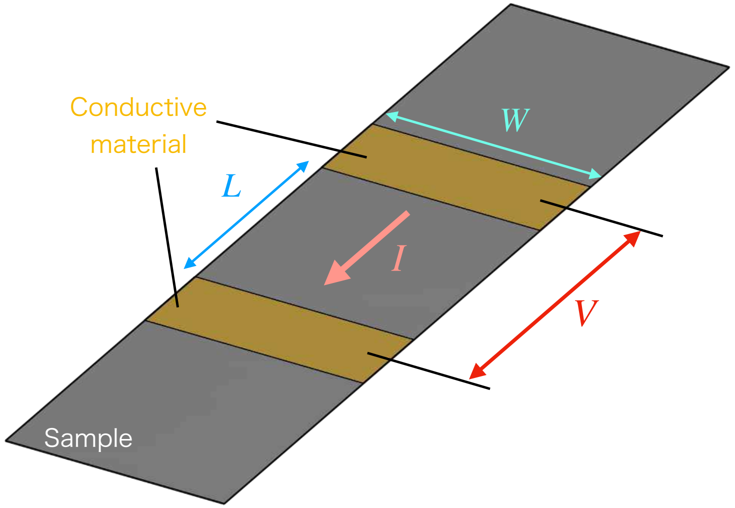




4 MHz/cm² at centre

Resistivity measurement

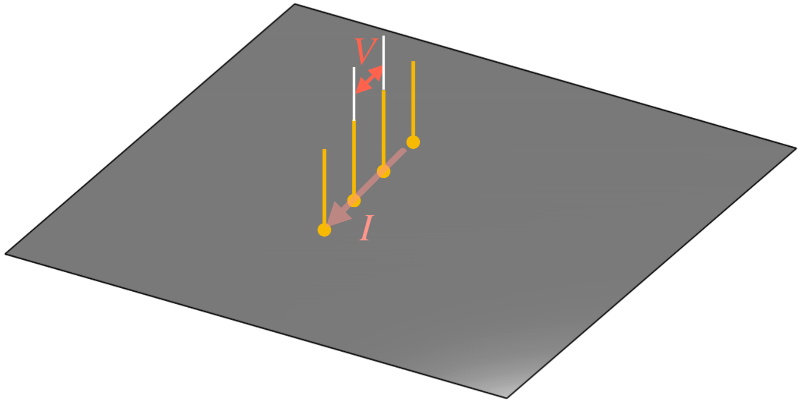
2 points method



- Surface resistivity is calculated by

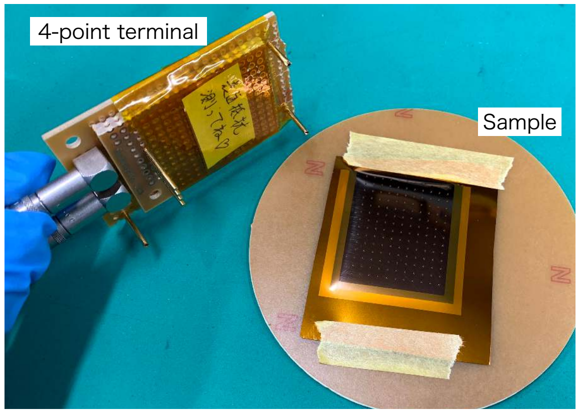
$$\rho_S = \frac{V}{I}\frac{W}{L}$$

4 points method



- Surface resistivity is calculated by

$$\rho_S = \frac{V}{I}\frac{\pi}{\ln 2} = \frac{V}{I} \times 4.532$$

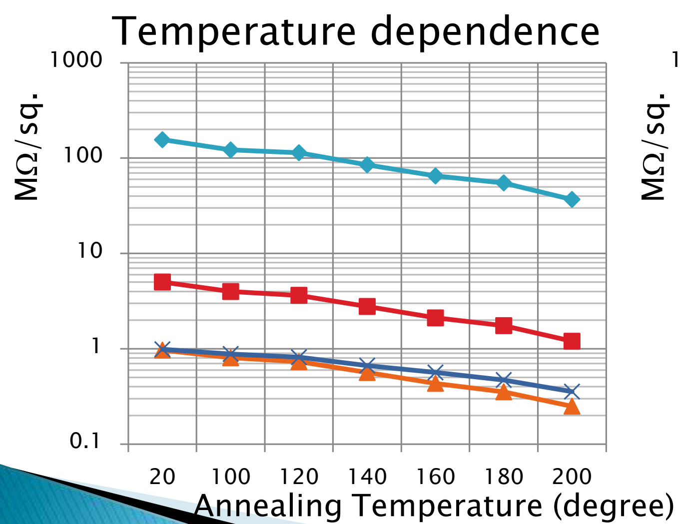


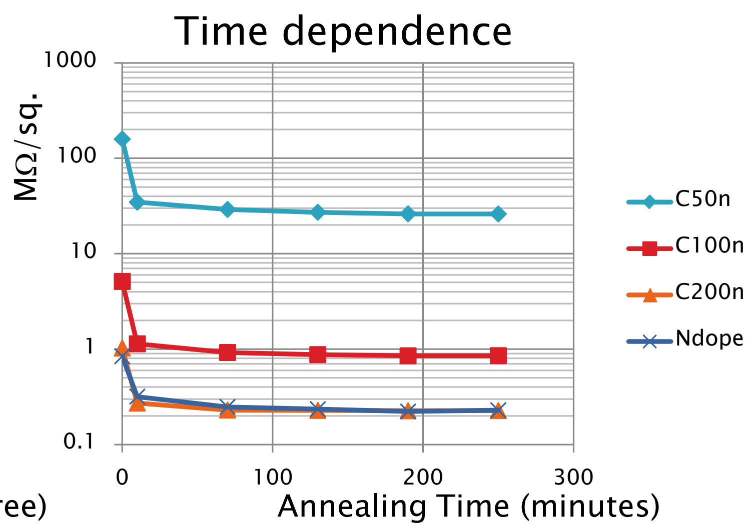
Heating test in Kobe

A. Ochi, Resistive DLC meeting in RD51, March 2020

Results for measurements

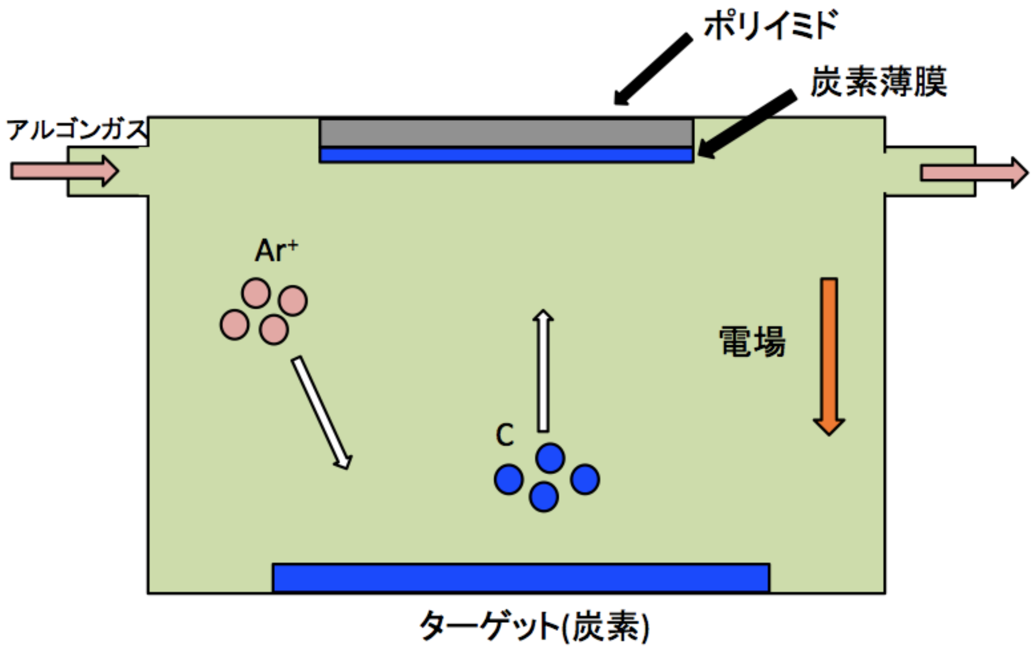
- All resistivity are measured under room temperature (18-19 degree) after annealing.

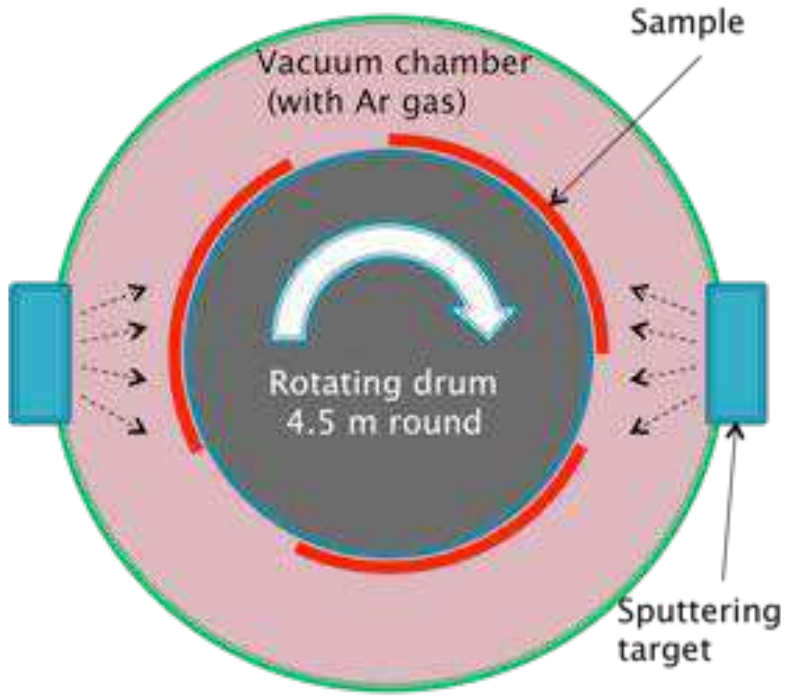




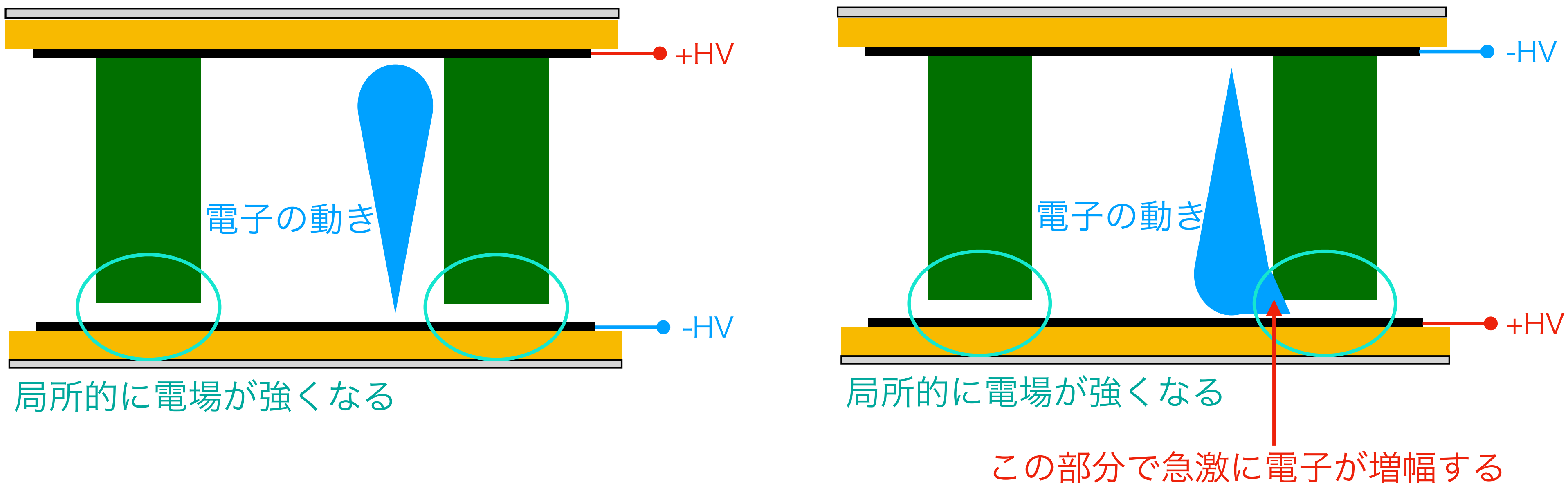
A.Ochi, Resistive DLC meeting 2020/3/26 6

Sputtering technology





Electrode polarisation



- Avalanche direction due to electrode polarisation
  - +HV: Need enough high resistivity
  - -HV: Not severe requirement to resistivity
    - Can be operated with <1 MΩ/sq

Possible schedule for installation

- Goal: Installation in 2023 physics run
  - Performance of RPC as upstream RDC will be evaluated in beam test