Polarimeter Detector development using GEM technology for Proton EDM Measurement

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RD51 collaboration meeting

Oct.16-17, 2015, Trieste/Italy

Introduction to CAPP/IBS

- Center for Axion and Precision Physics (CAPP) at Institute for Basic Science (IBS), http://capp.ibs.re.kr/html/capp_en/
- Located at KAIST campus in Daejeon, South Korea
- Establishing center (only two years of history)

We are working on:

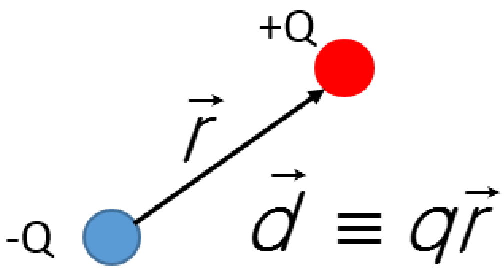
- **Axion-dark matter search**
  - Cavities, Cryogenics, Electronics, Super conducting magnet, SQUID, etc.
- **Storage ring Proton/Deutron EDM**
  - Polarimeter, Beam position monitoring (with magnetic shielding), Beam dynamics, etc.
- **Muon g-2 experiment**
  - System design, Systematics
- **Others**

Our detector lab is not ready yet.
→ Not much experiment results on detectors in this talk.

Outline

1. Introduction
2. Storage ring technique and spin precession measurement
3. Polarimetry
   - ✓ Spin precession measurement
   - ✓ Poarimeter detectors
4. Geant4 simulation
   - ✓ Proton scattering on Carbon target
   - ✓ Equal rate anode pad design
5. Current status of GEM detector development at CAPP/IBS
6. Summary

Intro/EDM and CP violation

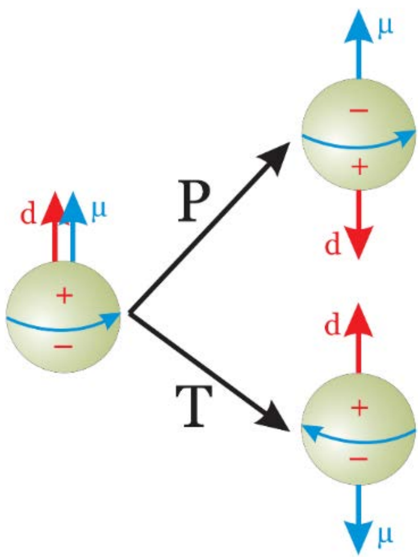


❖ P, T violation due to an EDM

$$H = -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E}$$

$$T(\vec{B},\vec{\sigma}\ change): H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$P(\vec{E}\ change): H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$



A nonzero particle EDM violates P, T, and assuming CPT conservation, also CP violation.

Searching EDM

- Motivation
  - ✓ Strong CP problem, Θ_{QCD}
  - ✓ Matter-antimatter asymmetry (Baryogenesis)
- Current EDM bounds
  - ✓ SM predict non-vanishing EDM
    - $|d_e| < 10^{-38}$ e.cm
    - $|d_{n,p}| < 10^{-32}$ e.cm
    - Beyond current experiment limit
  - ✓ SUSY prediction: up to $3\text{x}10^{-26}$ e·cm (nEDM limit)
  - ✓ Neutron EDM bound: $|d_n|<2.9\text{x}10^{-26}$ e.cm ('06)
  - ✓ Proton EDM bound: $|d_p|$ $<7.9\text{x}10^{-25}$ e.cm ('09)
  - ✓ Electron EDM bound: $|d_e|$ $<8.7\text{x}10^{-29}$ e. cm ('14)
- Target sensitivity level in the storage pEDM experiment
  - ✓ High statistics (10^{11} protons/store) is achievable using storage ring
  - ✓ Goal **10^{-29} e·cm** (statistical limit in about one year)
  - ✓ → 10^{-30} e·cm (with an upgrade)
- Physics reach $>10^3$ TeV

✓ The first EDM experiment started by Smith, Purcell and Ramsey in 1951 (and published in 1957) obtaining a limit of $|d_\text{n}| < 5 \times 10^{-20}$ e·cm.

Storage ring technique for EDM search

$$\frac{d\vec{S}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E} \qquad \vec{d} = \frac{\eta e}{2mc}\vec{s}, \vec{\mu} = \frac{ge}{2m}\vec{s}$$

The g-2 precession in the presence of both *B&E*-fields for $\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$

$$\vec{\omega}_a = -\frac{q}{m}\left\{a\vec{B} - \left[a - \left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}\right\}$$

anomalous magnetic moment a=(g−2)/2.

G-2 precession in **pure electric ring (Yannis Semertzidis)→** $\vec{\omega}_a = \frac{q}{m}\left[a - \left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}$

for the proton (a=1.792847357(23)) >0

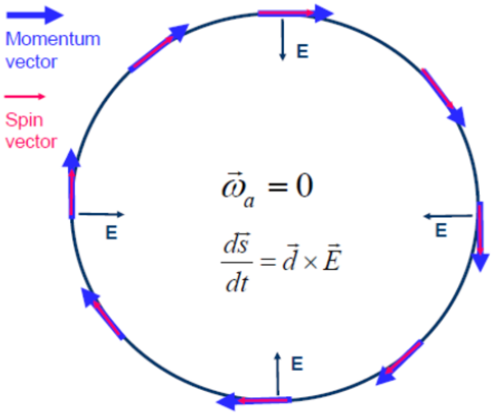
$\vec{\omega}_a = 0 \;\; at \;\; p = \frac{m}{\sqrt{a}} = 0.700740$ GeV/c :**magic momentum**

Spin freezes to the momentum direction at the magic momentum!

→ **Frozen spin method**

→ No precession on the ring plane

Now, spin precesses on the vertical plane! $\vec{\Omega}_{EDM} = -\frac{e\eta}{2m}\frac{\vec{E}}{c}$

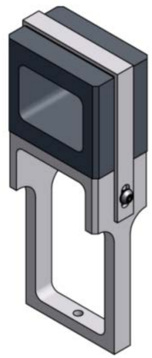


For a<0, no magic momentum

Need E field for the same effect → $E = \frac{aBc\beta\gamma^2}{1 - a\beta^2\gamma^2} \approx aBc\beta\gamma^2$

How to measure spin precession?

- Store polarized beam in the storage ring (10^{11} protons)
- Extract the beam slowly (in 10^3s for pEDM experiment)
  - ✓ by lowering the vertical focusing strength or
  - ✓ excite beam using white noise
- Spin-Orbit interaction (p-C scattering)→ hit count asymmetry on the detectors
  - ✓ L/R: vertical polarization
  - ✓ U/D: horizontal polarization
- Measure the asymmetry using a polarimeter



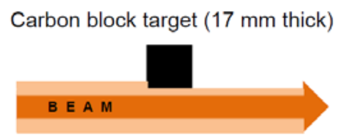
COSY carbon tube target

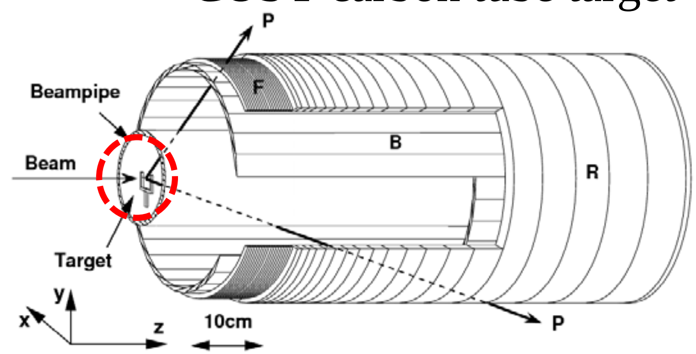
- For spin 1/2 particle

$$\sigma(\theta) = \sigma_{unpol}(\theta)\left[1 + P_y A_y\right]$$

$$L/R \ asymmetry \quad \varepsilon_{LR} = P_y A_y = \frac{L-R}{L+R}$$

$$P_y = \frac{1}{A_y}\frac{L-R}{L+R}$$





P_y is calculated from the asymmetry with known A_y

COSY EDDA detector
FZJ, Juelich, Germany

Spin precession rate

11.1 Expected signal of the pEDM experiment

***From pEDM proposal**

The expected EDM signal, assuming the spin is along the momentum, is estimated by

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} \Rightarrow \frac{1}{2}\hbar\omega = dE \Rightarrow \frac{d\theta}{dt} = \frac{2dE}{\hbar} \Rightarrow$$
$$\theta(t) = \theta_0 + \frac{2dE}{\hbar}t, \qquad (11.1)$$

where d, E are assumed to be orthogonal to each other. For E=10.5 MV/m, 95% E-field coverage of the ring, and an EDM of d=10^{-29} $e\cdot$cm, the rate of change in the vertical spin component is

$$\theta(t) = \theta_0 + \frac{2dEc}{\hbar c}t = \theta_0 + \frac{2\times10^{-31}\,\mathrm{e\cdot m}\times10.5\mathrm{MV/m}\times0.95\times3\times10^{8}\mathrm{m/s}}{197\ \mathrm{MeV\ fm}}t \Rightarrow$$
$$\theta(t) = \theta_0 + 3\frac{\mathrm{nrad}}{\mathrm{s}}t.$$

We can make the following observations from equations (11.1) and (1

- In pEDM experiment, spin processes on the vertical plane.
- The storage time will be 1000 s.
- EDM signal of **~3 μrad/1000s**
  - ✓ Projected systematic error << 1 ppm
  - ✓ Need long spin coherence time
  - ✓ **Already achieved >1000 s SCT (COSY)**

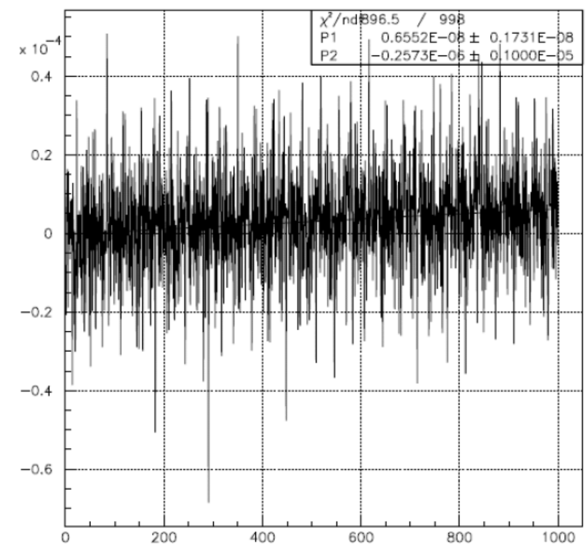


Figure 11.1: (L-R)/(L+R) vs. time [s], is as well as the fit results to two parameters (slope and dc offset). The total counts used are 4×10^{12}, with P_0=0.8, and A=0.6. The slope is estimated with 3.8 sigma statistical accuracy. The fit results confirm the result of eq. (11.3).

Statistical error of L/R asymmetry (statistical sensitivity)

$$\varepsilon_{LR} = \frac{L-R}{L+R} = p_y A_y(\theta) \quad \Rightarrow \quad \sigma_{LR} \approx \frac{1}{\sqrt{2N_0}} = \frac{1}{\sqrt{L+R}} \propto \frac{1}{\sqrt{it}}$$

i : beam current, t : measurement time

More realistic expression of statistical error is

$$\sigma_{LR} = \frac{2\hbar}{PAE\sqrt{N_{tot} f T_{tot} \tau_p}}$$

where P is the degree of polarization, A analyzing power and E is the electric field causing the spin precession. If we use the parameters $P = 0.8$, $A = 0.6$, $E = 10.5$ MV/m, $N_{tot} = 4 \times 10^{10}$ particles/storage, an effective detection efficiency of $f = 0.011$, total running time $T_{tot} = 10^7$ s/year, and spin coherence time of $\tau_p = 10^3$ s, the resulting statistical error is **~1.8×10^{-29} e.cm per year**.

Statistical errors and figure of merit

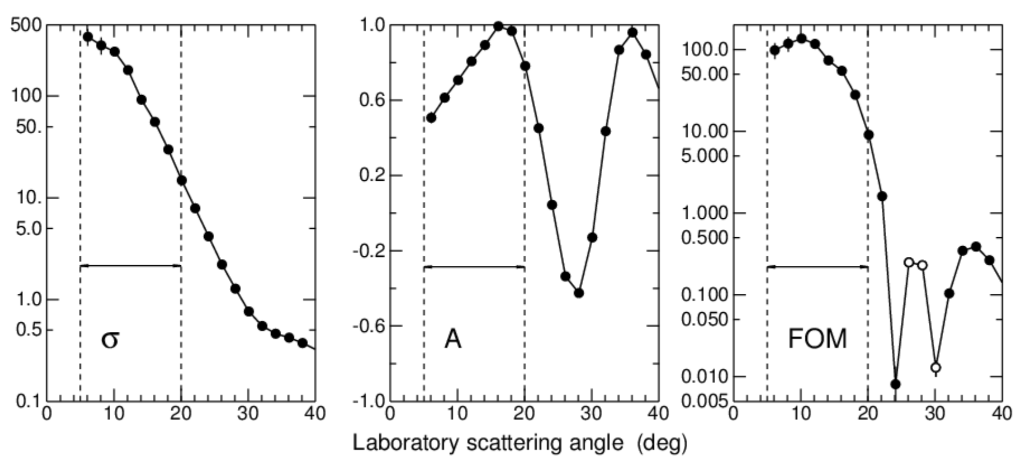
L/R asymmetry $\varepsilon_{LR} = \frac{L-R}{L+R} = p_y A_y(\theta)$

The uncertainty in the asymmetry is given by

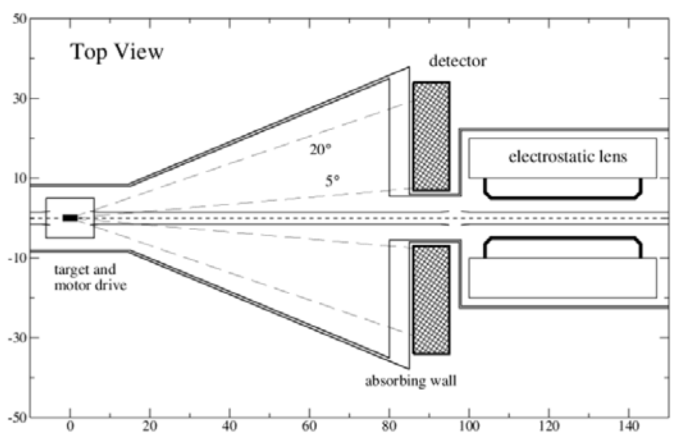
$$\sigma_{p_y}^2 = \frac{\sigma_{LR}^2}{A_y^2} = \frac{1}{2N_0 A_y^2}$$

The denominator is called the 'figure of merit'.

$$FOM \equiv \sigma A^2 \quad \leftarrow 2N_0 \propto \sigma : \mathit{differential\ cross\ section}$$

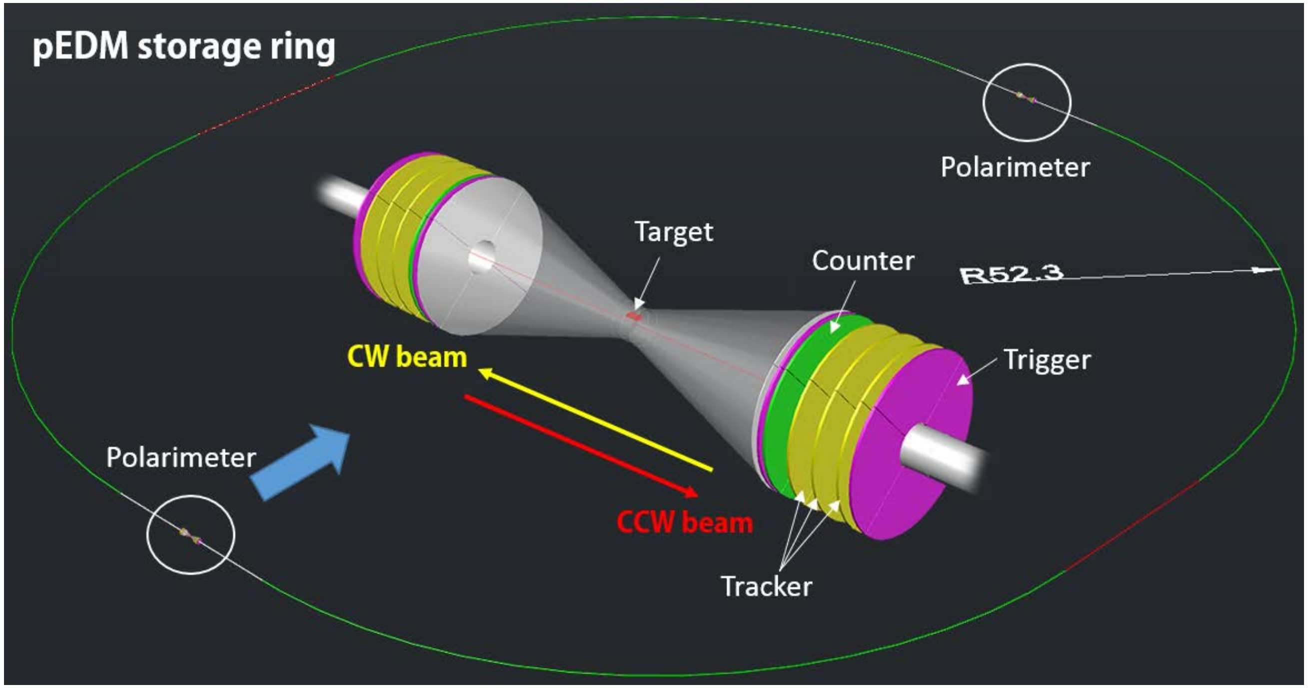


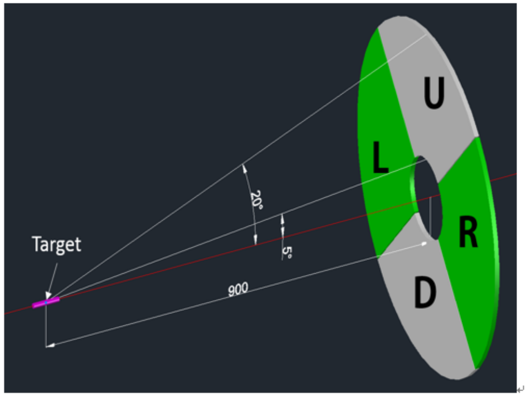
Optimum angle (FOM) range: 5~20 deg.

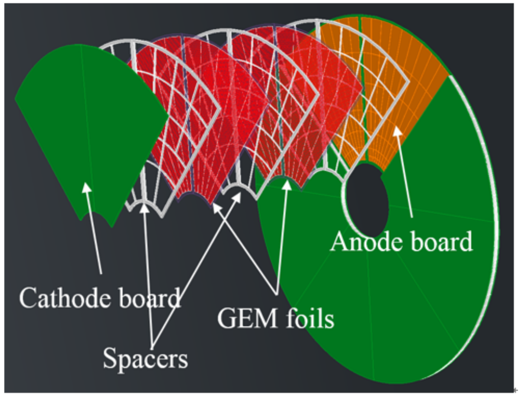


pEDM polarimeter
(from pEDM proposal)

GEM-based prototype polarimeter detector concept

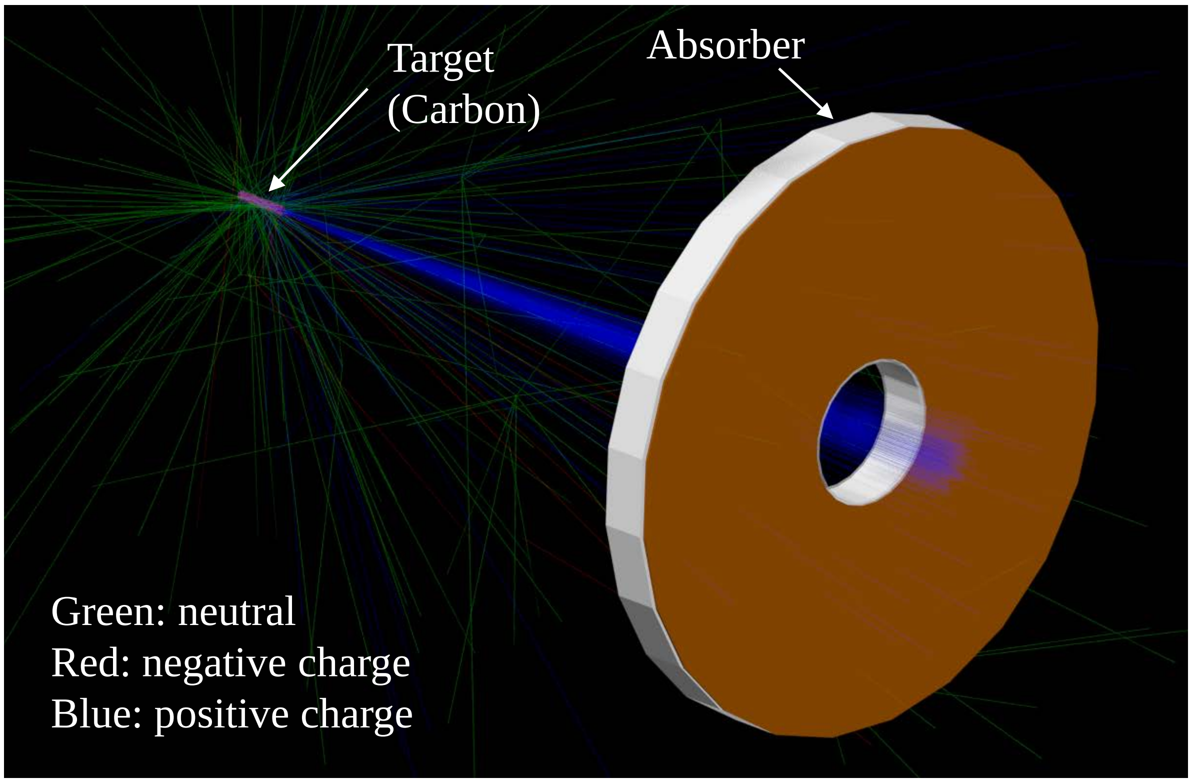




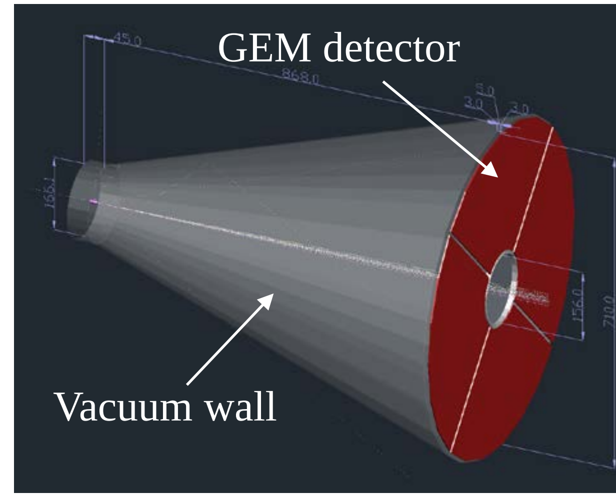


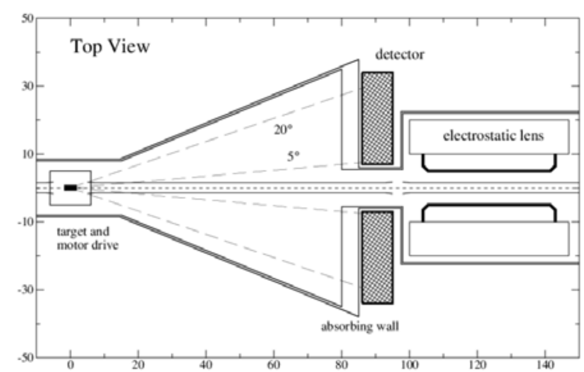
GEM-based prototype polarimeter detector concept

MC simulation



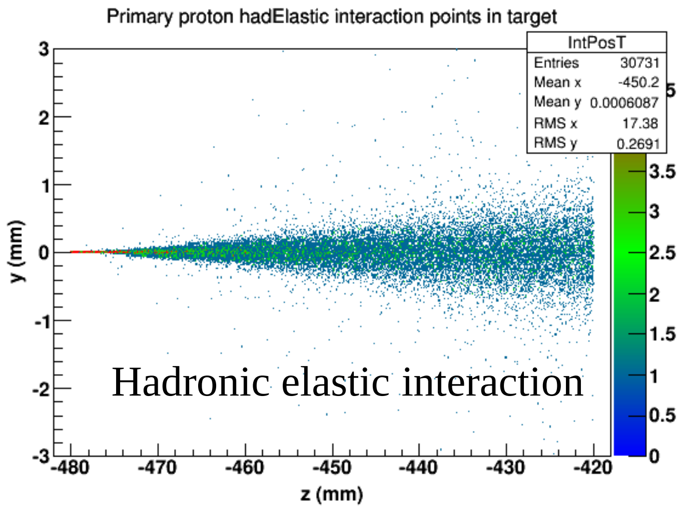
From Geant4 visualization

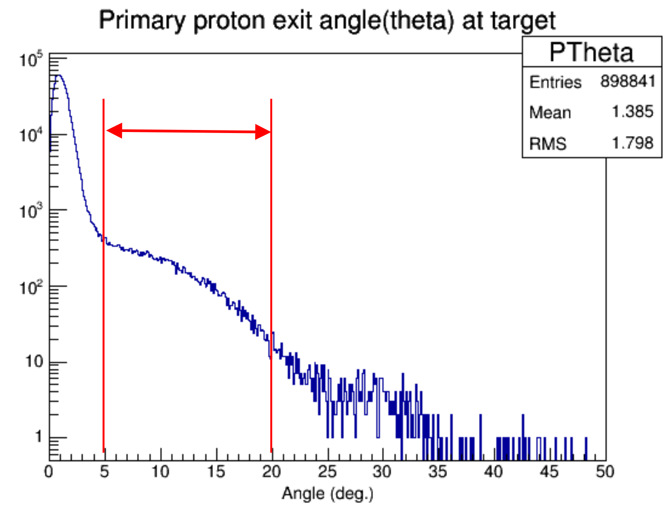


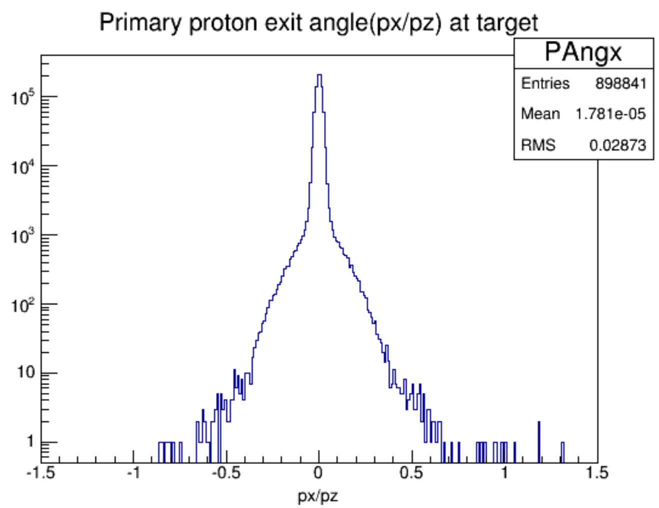


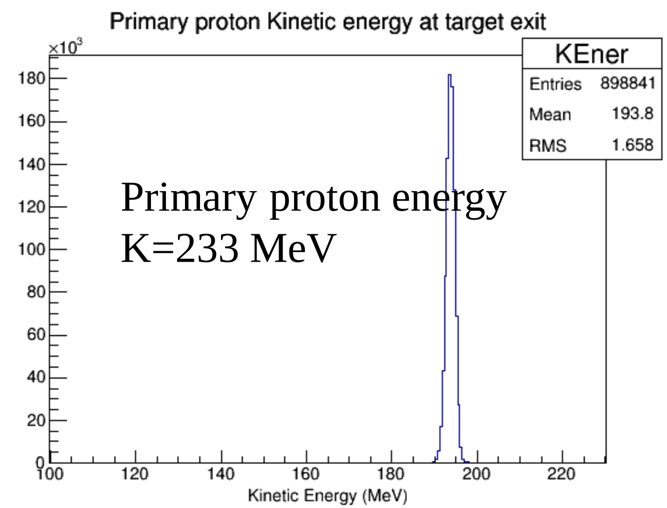
Detector acceptance angle: 5~20^{o}

Proton interaction in Carbon target





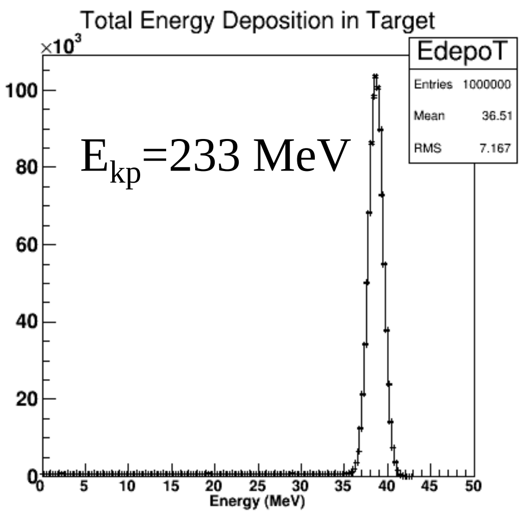


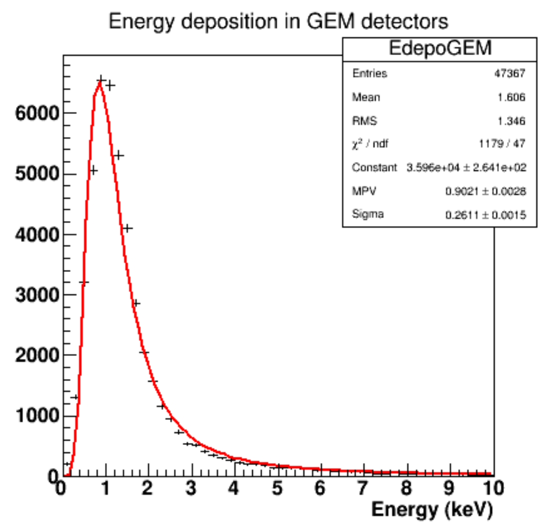


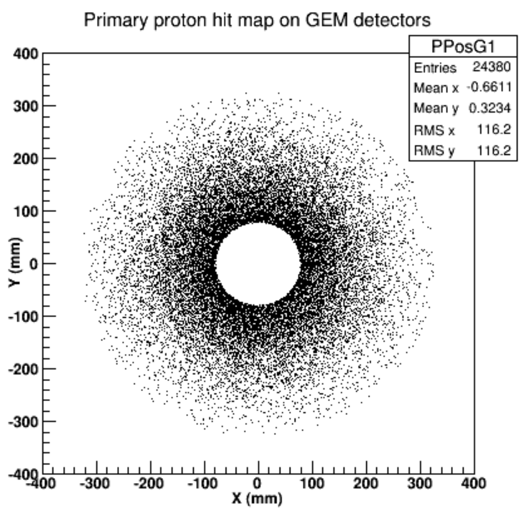
101159 protons out of 1000000 are absorbed in the target.(10.12%)

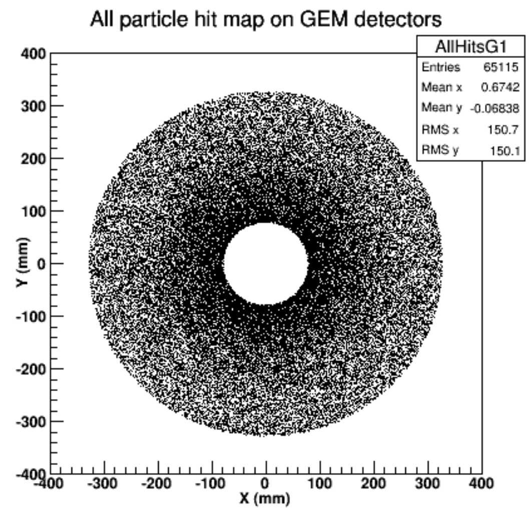
Target length=60 mm

Energy deposition and hit map in the detector







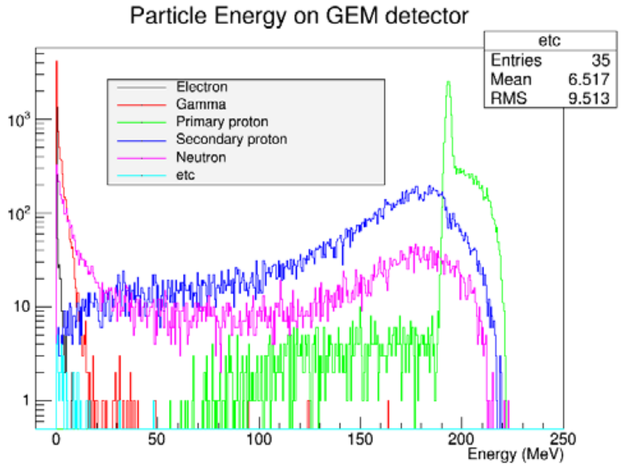


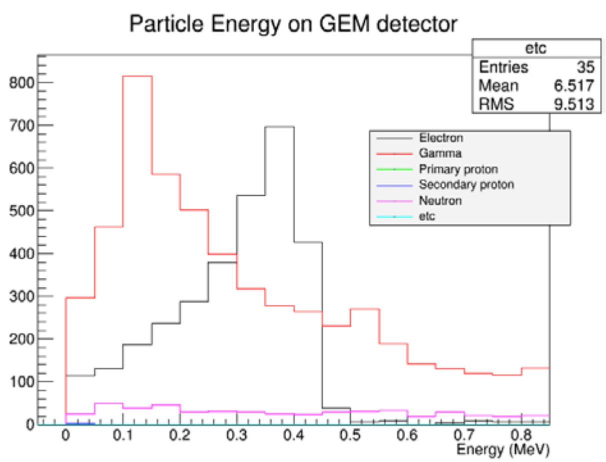
Hits by primary protons only
Detector acceptance : 2.4 %

All hits including secondaries
Detector acceptance: 6.5 %

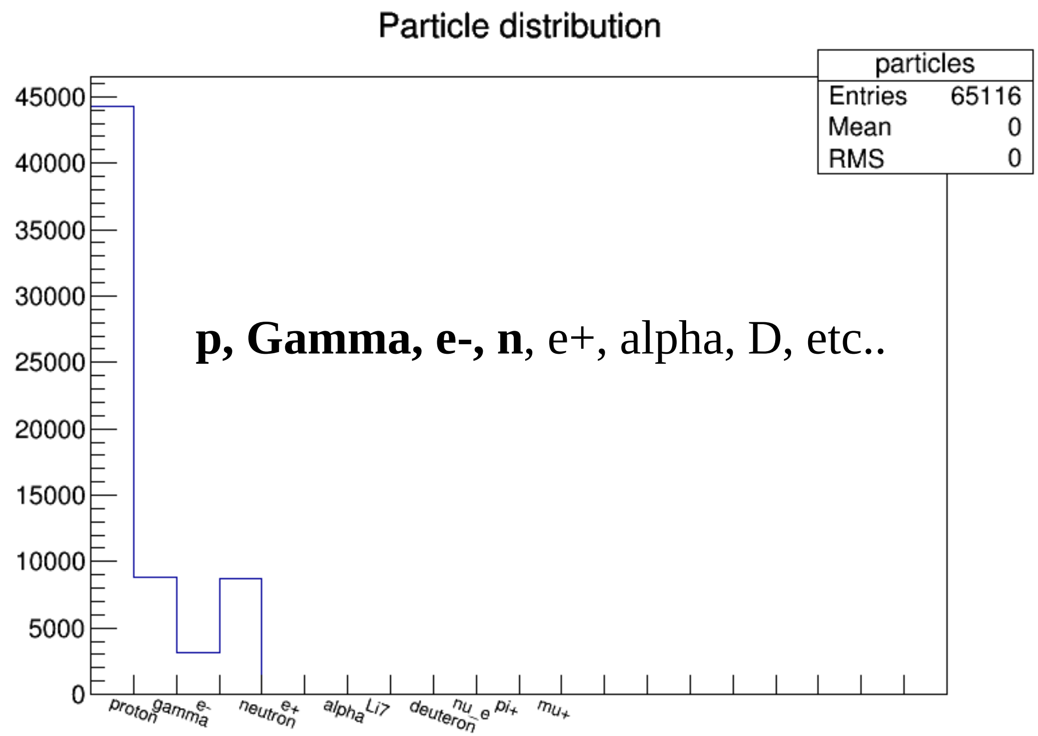
→170% of back ground signals from the other secondary particles.

Particles on the detector plane





Low energy region



Particles arriving on detector plane

$ArCO_2$=80:20

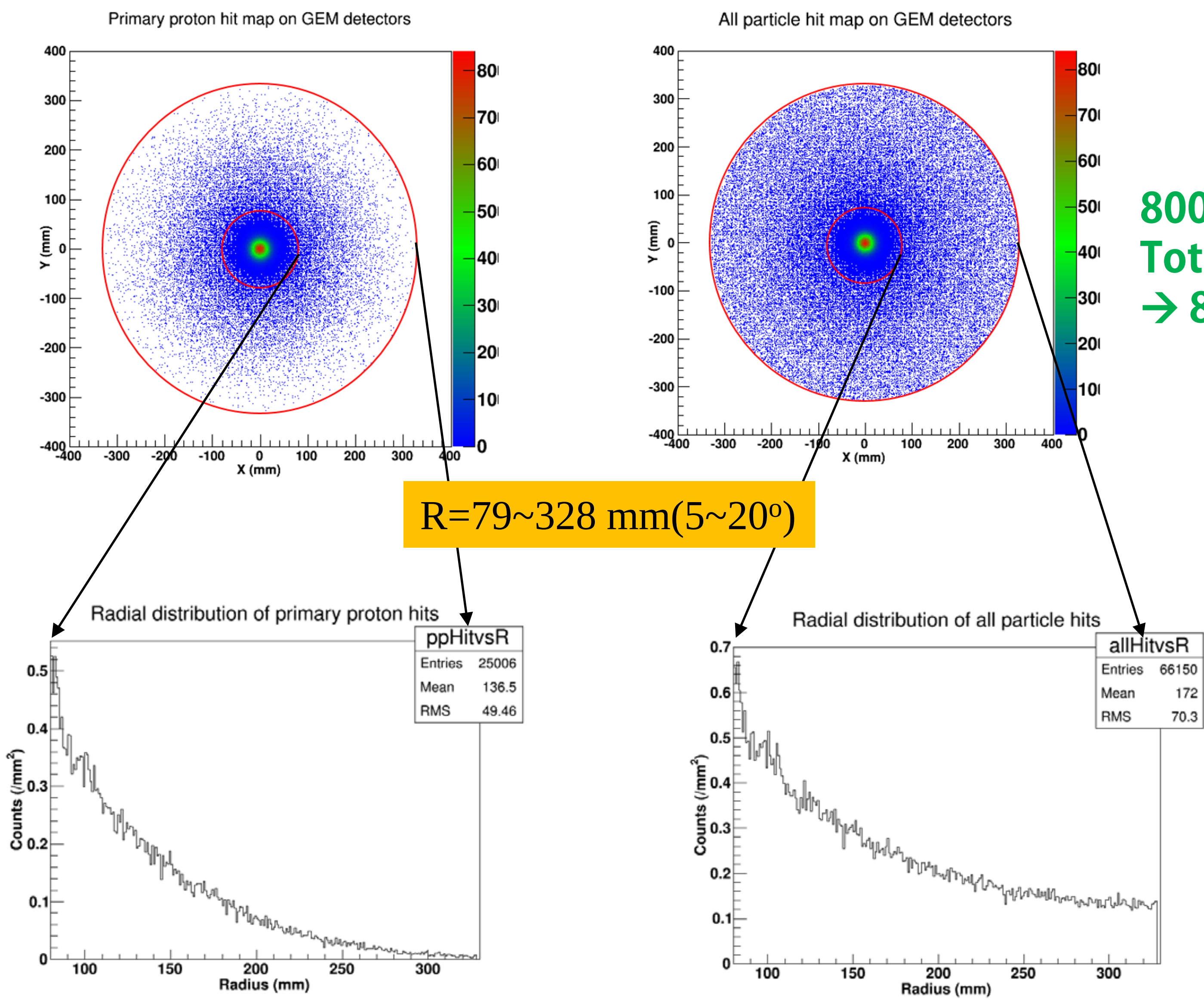
About detector counting rate

Beam parameters:

1. 701 MeV/c protons (E_k=233 MeV, β=0.6→v=1.8×10^8 m/s)
2. Ring circumference 500 m.
3. Revolution frequency is about 0.36 MHz.
4. About 100 bunches
   - ✓ 5 m between bunches
   - ✓ 28 ns bunch spacing
   - ✓ 0.36MHz x 100=3.6×10^7 bunches/s
5. 5×10^{10} particles/storage
   - ✓ 5×10^8 particles/bunch
6. 4 polarimeters on the ring for CW/CCW beams

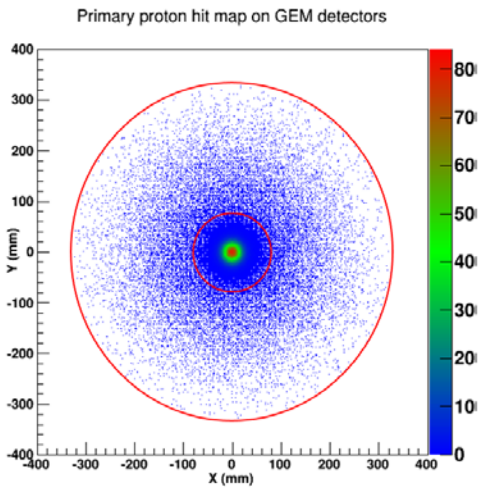
- ✓ **Beam extraction for 1000s**
- ✓ **Assuming full extraction at the constant extraction rate for the entire extraction**
  - **5×10^7 interactions/s**
- ✓ **$5\times10^7/3.6\times10^7$=1.4 interactions/bunch**
- ✓ **Assume 6.5 % of detector acceptance(including BG, from simulation)**
  - **3.25×10^6 hits on detector plane/s → need high speed DAQ system**
  - **4 detectors(1024x4=4096 channels) →800 hits/ch/s (including BG)**
- ✓ **For signal(2.4 % acceptance) →300 hits/ch/s (signal)**

Particle hit map(counts/mm²) at the detector location



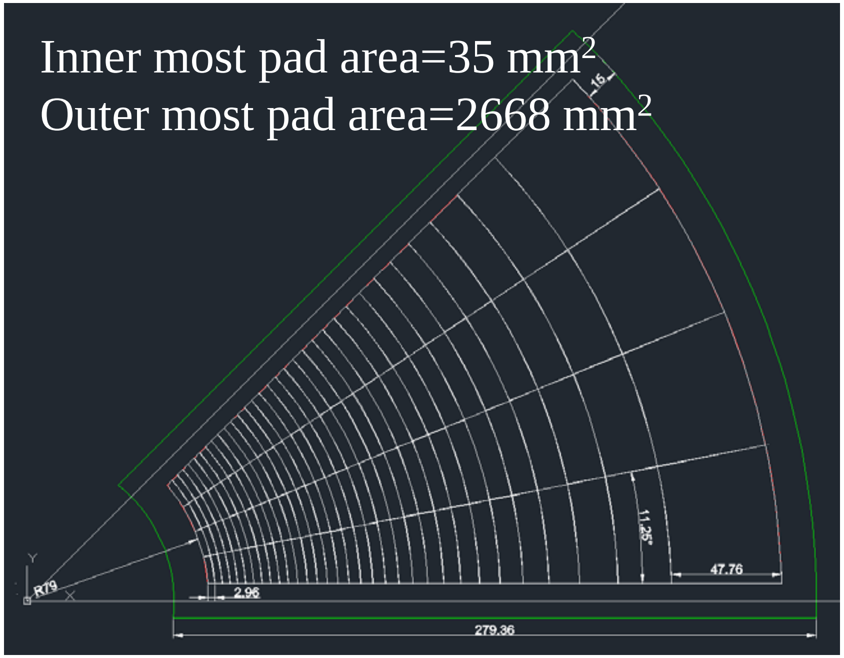
800 hits/ch/s
Total 1024 chs
→ 820 kHz/s

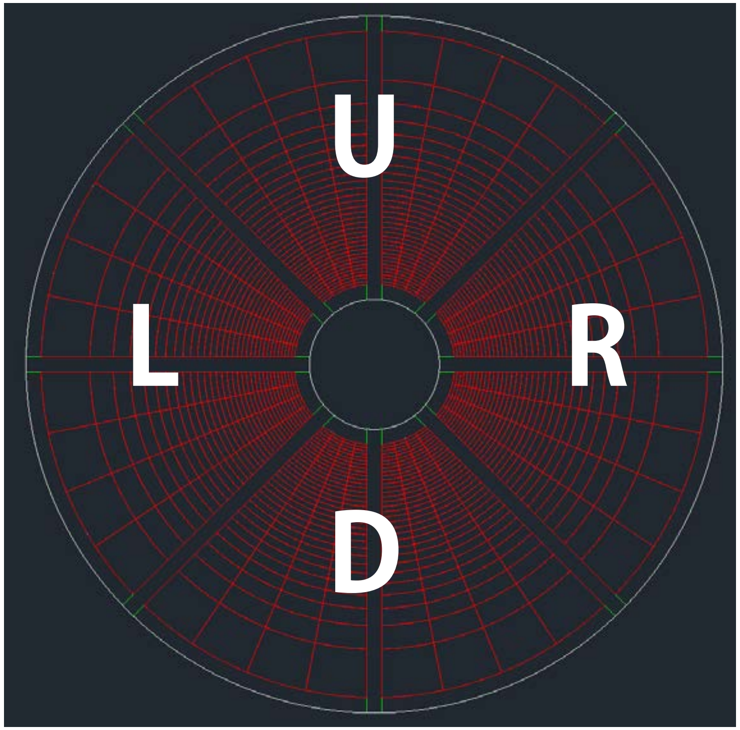
Equal rate anode pads/Primary proton only



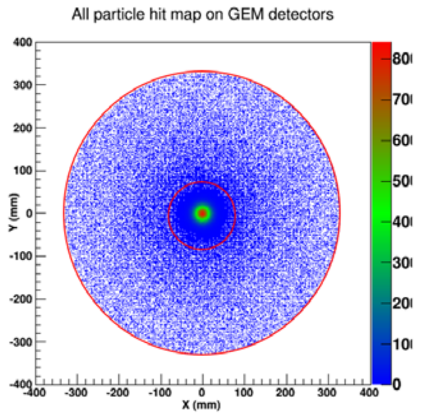
- 128 ch/octant
- 8 octants/polarimeter(counter)
- 1024 ch/polarimeter
- 300 Hz/ch(for signal)

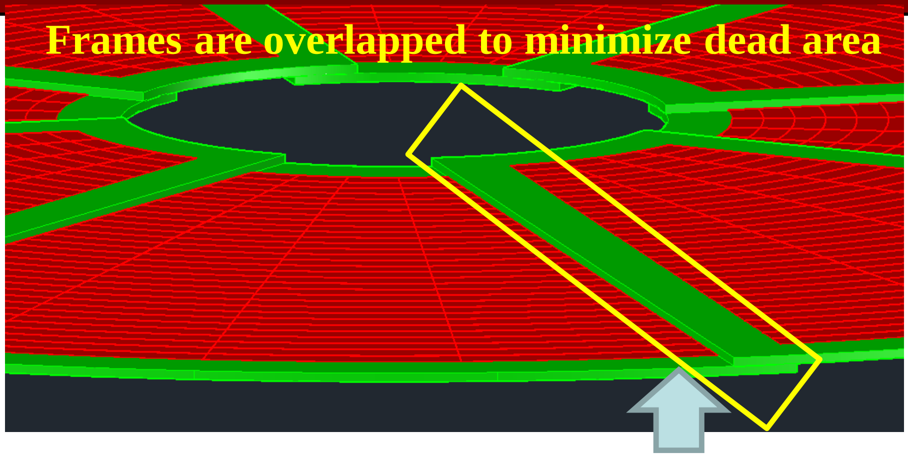
Counting rate on the inner most pad=857 Hz/cm^2
Counting rate on the outer most pad=11 Hz/cm^2

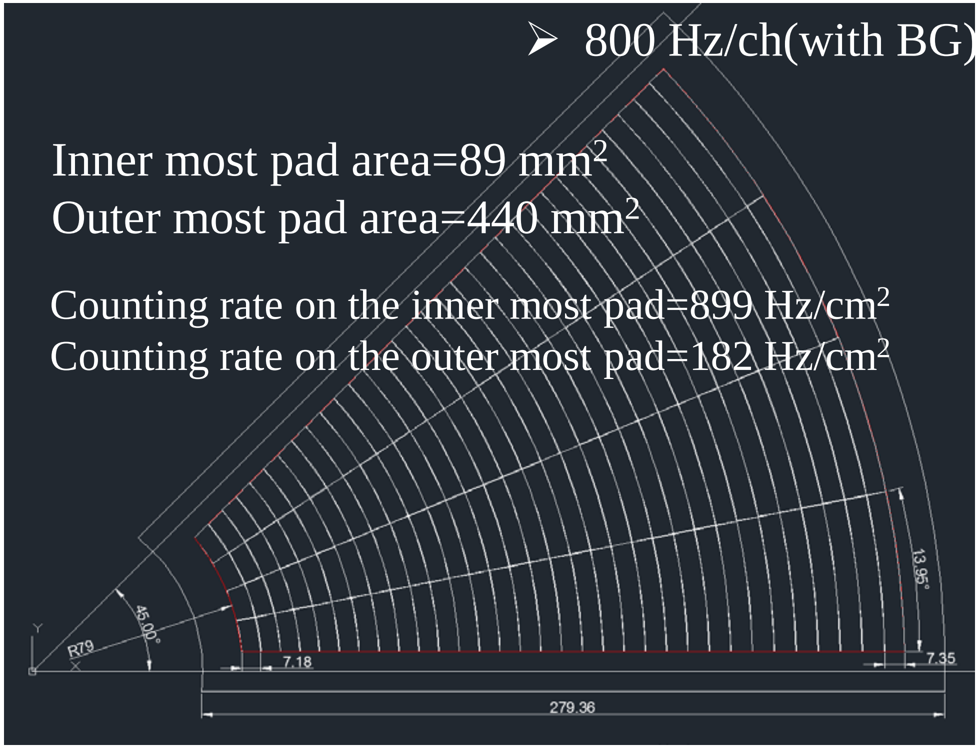




Equal rate anode pads/BG included



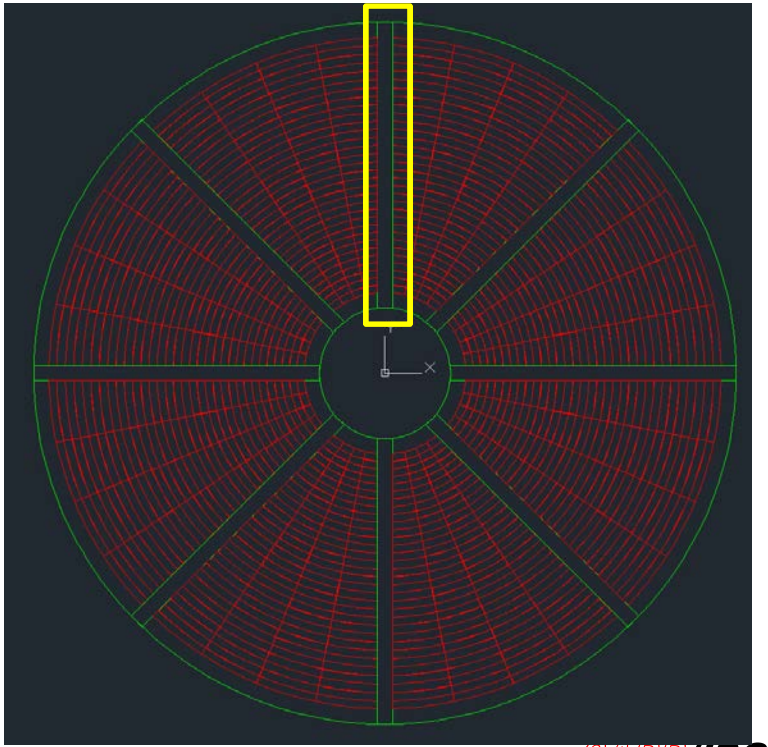




- 800 Hz/ch(with BG)

Inner most pad area=89 mm^2
Outer most pad area=440 mm^2

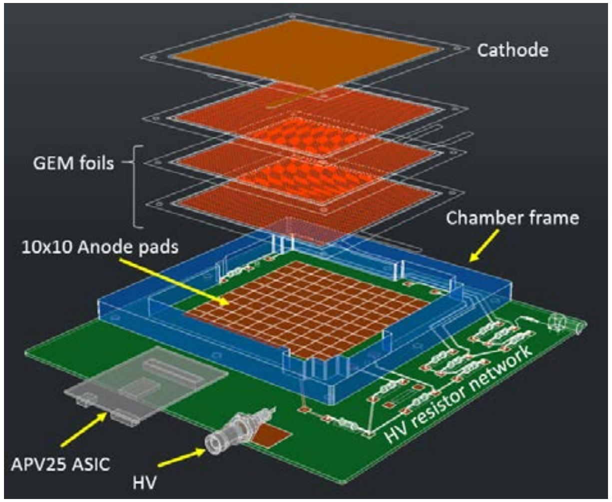
Counting rate on the inner most pad=899 Hz/cm^2
Counting rate on the outer most pad=182 Hz/cm^2



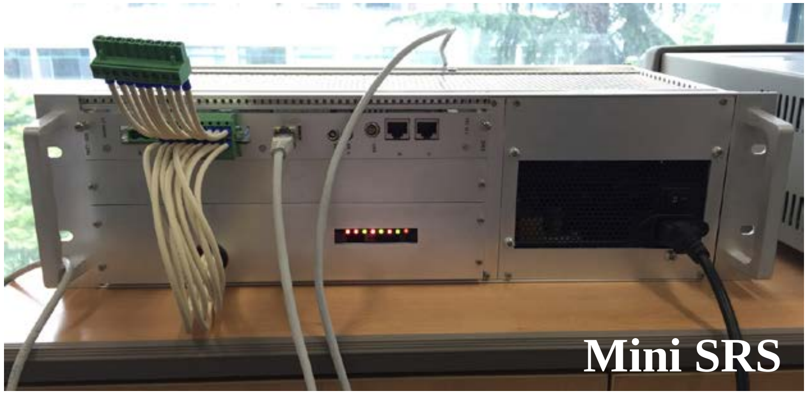
Current status of GEM detector development

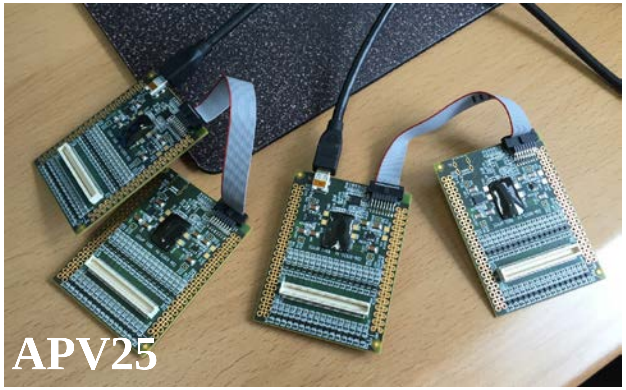
- Preparing lab.
  - ✓ Clean room
  - ✓ Gas distribution system
- MC simulation study of proton scattering on carbon target
- GEM detector design and construction
  - ✓ 10x10 cm^2 test chamber design finished
- Working with CERN GDD lab. on DAQ system preparation
  - ✓ Many thanks to Hans Muller and Rui De. Oliveira for the help during the purchase process
  - ✓ Many thanks to Eraldo Oliveri and CERN GDD group for the help on the SRS use!

10x10 test GEM detector



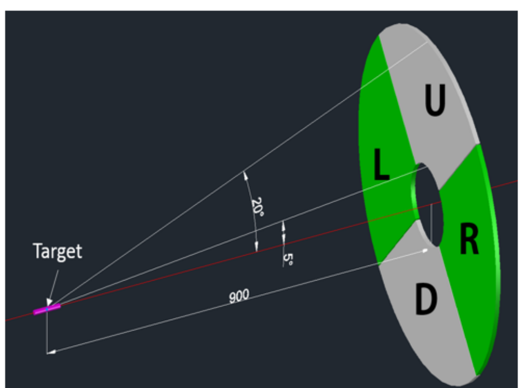
Being produced at CERN

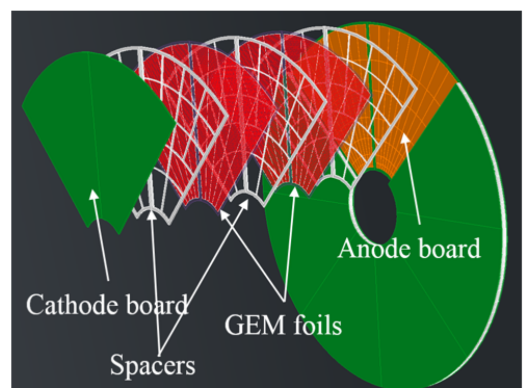




Summary and plans

- We (CAPP/IBS) are developing GEM detectors as polarimeter detectors for pEDM experiment
- RD51 SRS as the DAQ system
  - ✓ Being tested with APV25
  - ✓ will be replaced with VMM
- Lab. is under preparation at CAPP/IBS, Korea
- Cooperating with CERN PCB workshop for GEM foils, GEM chamber and anode board production
- The first 10x10cm^2 test chamber is almost ready
- The prototype detector design and production will be finished next year





Center for Axion and Precision Physics (CAPP/IBS, KAIST)

We are working on:

- **Axion search**
- **Proton/Deutron EDM**
- **Muon g-2 experiment**
- **Etc.**

Thank you!

http://capp.ibs.re.kr/html/capp_en/

Located at KAIST campus in Daejeon, South Korea