Detector R&D Activities for CMS and RAON

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on behalf of the Korea University Group

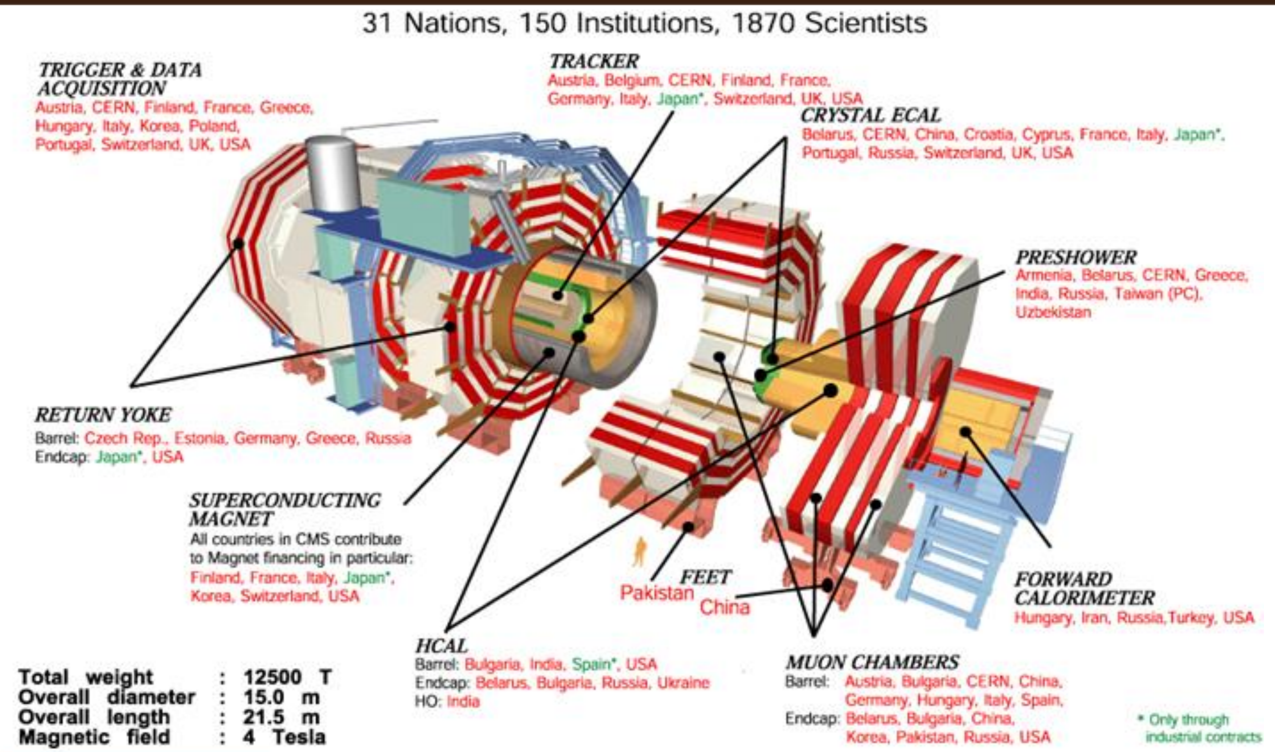
Contents

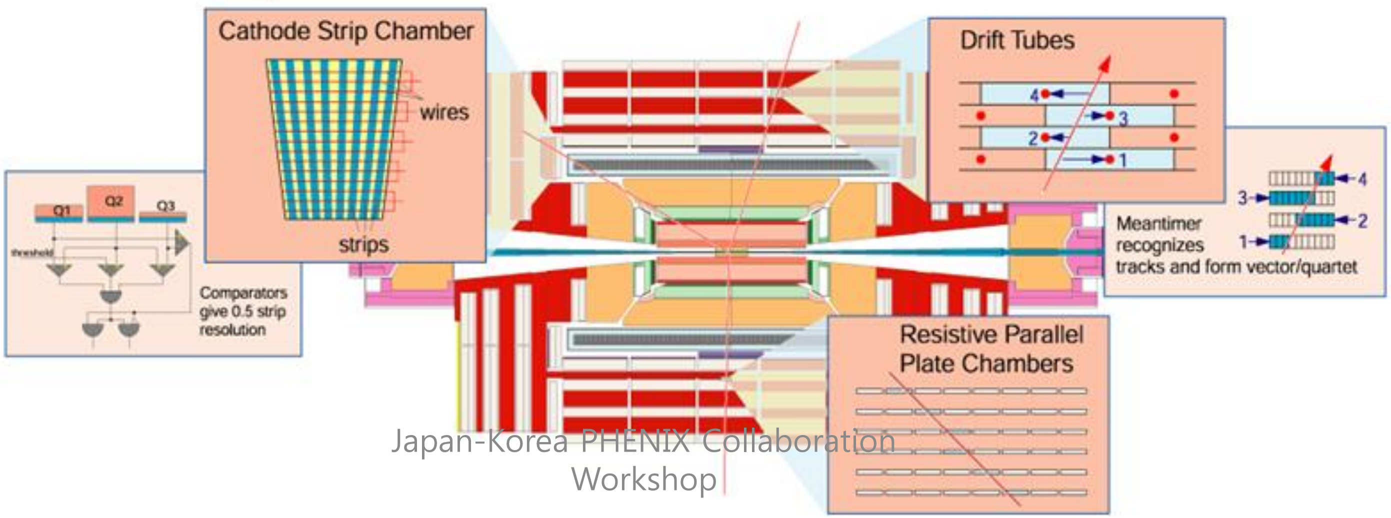
MRPC: PHASE II upgrade for CMS/LHC

Gaseous Detectors in CMS

Trackers :
- Drift Tubes (Barrels)
- CSCs (Forwards)

Triggers :
- RPCs





1. RPCs System for the Compact Muon Solenoid

(CMS/TDR LHCC/CERN 97-32)

- RPCs in Barrel + Endcap cover η < 2.1
- The angular coverage ~ 3 π

Barrel RPCs

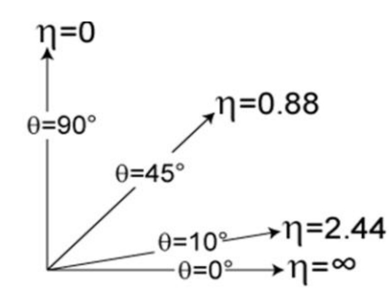
- 6 stations (layers)
- Fully covering up to η = 0.8
- Partially covering up to η = ~ 1.2

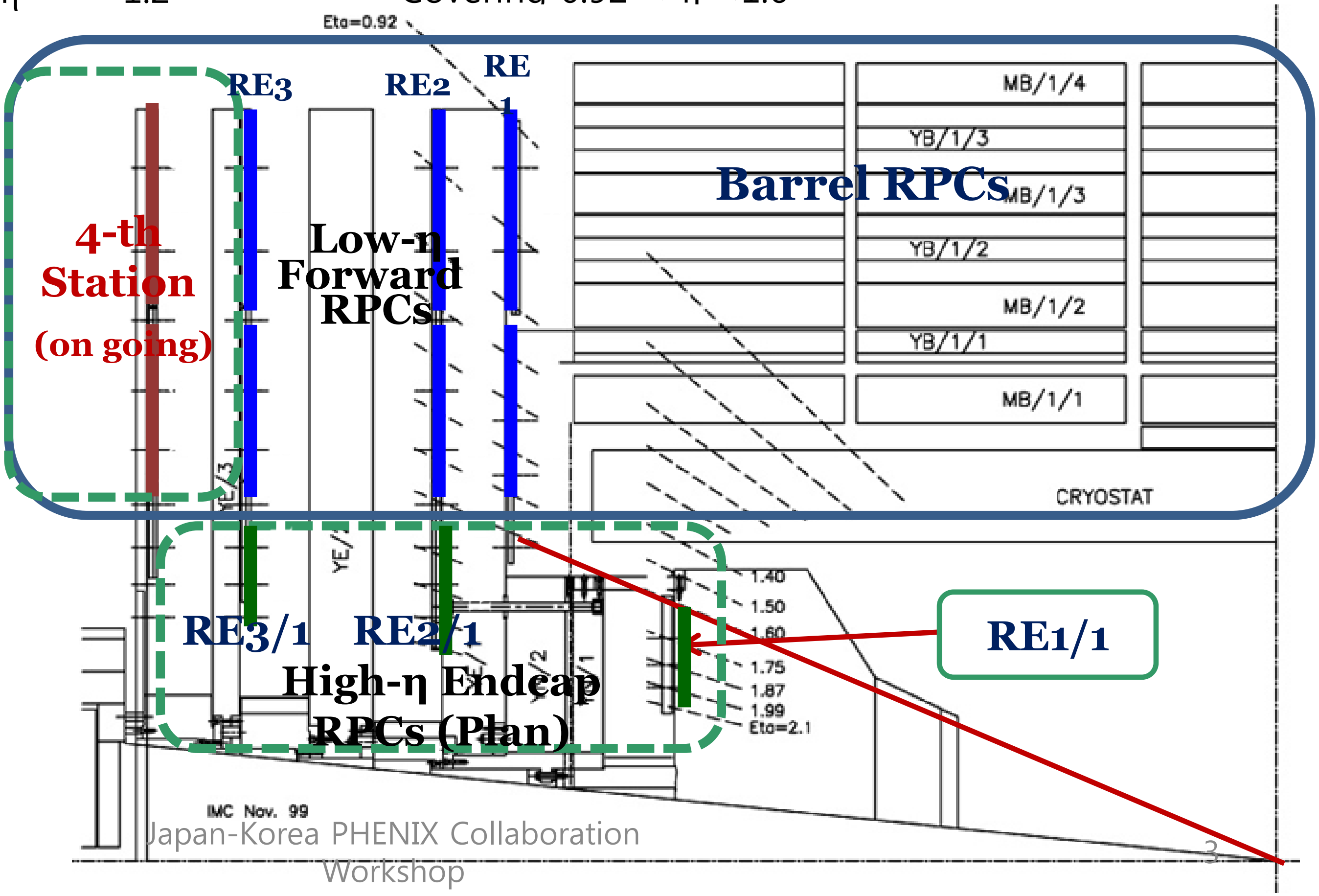
Endcap RPCs

- 2 wings (RE+, RE-)
- 4 stations (RE1, RE2, RE3) in each wing
- Covering 0.92 < η <1.6

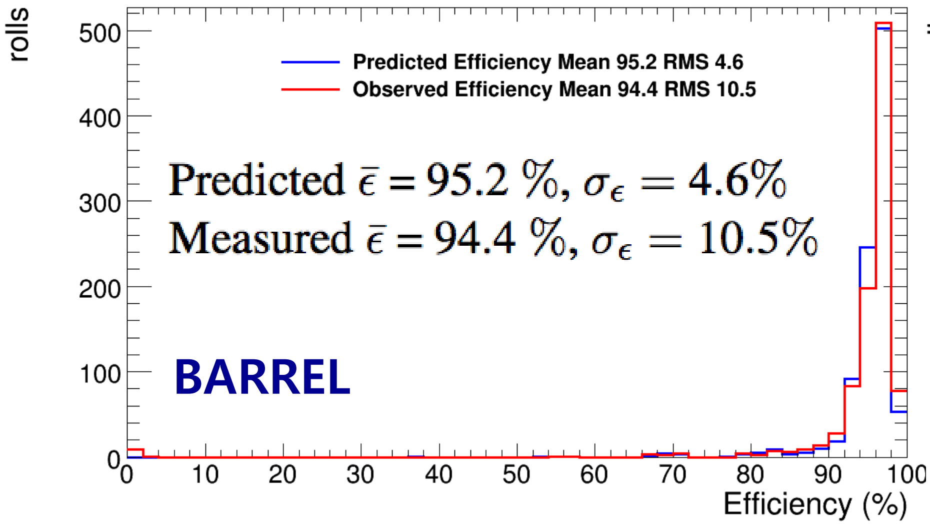
$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_{\mathrm{L}}}{|\mathbf{p}| - p_{\mathrm{L}}}\right)$$

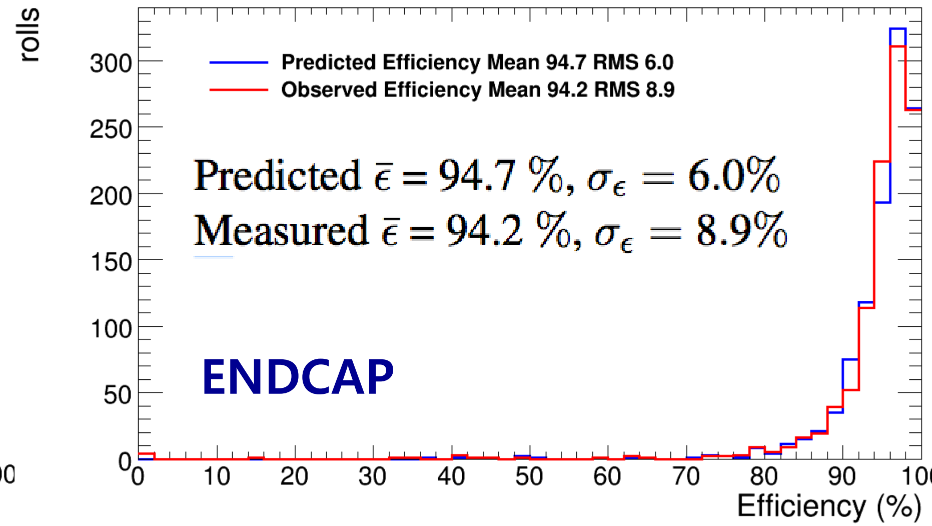
$$v \rightarrow c \quad \eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



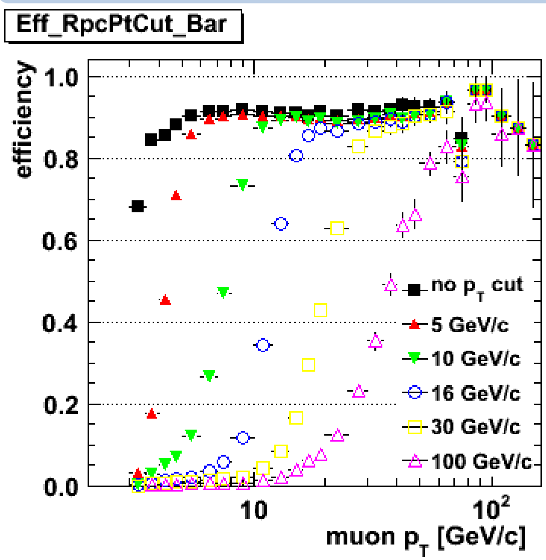


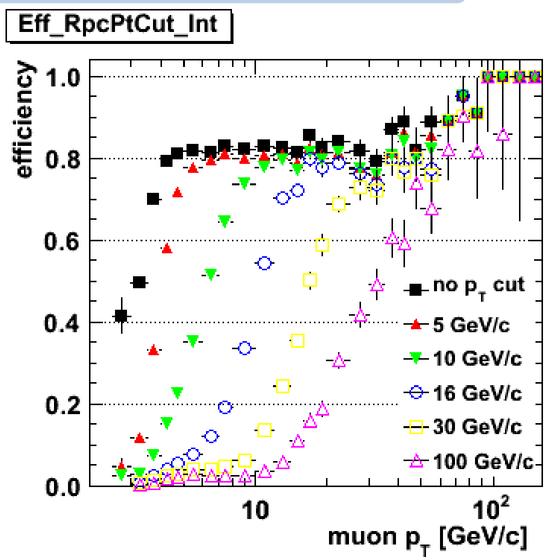
Muon trigger performances of the current double-gap RPC system

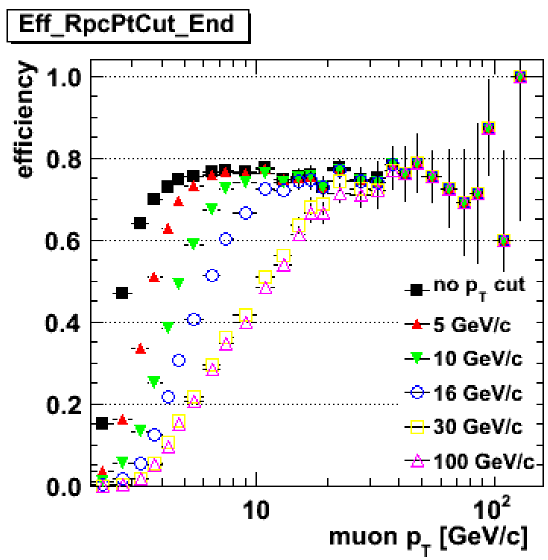




Efficiencies for single muons for various p_T selections







Geometrical inefficiency is also included

2. PHASE I upscope: 4-th RPC station RPC system

CMS RPCs originally proposed in the LHCC-97-32

- 6 RPC stations in BARRAELs in 0.0 <|η|< 0.92
- BARREL + ENDCAP cover 0.92 <η< 1.1
- 4 RPC stations in ENDCAP in 1.1 <|η|< 2.4

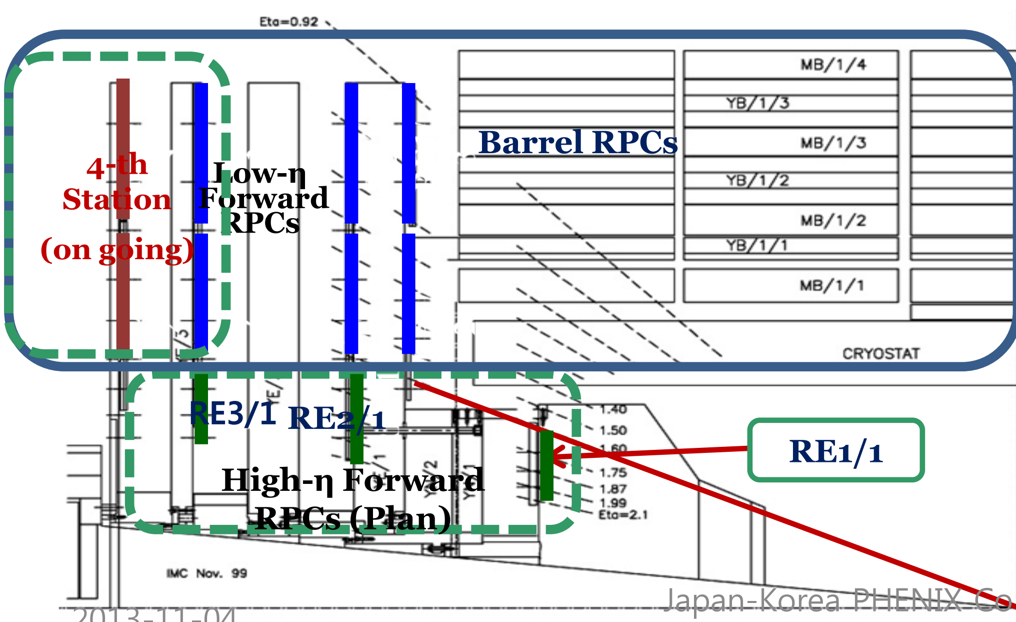
In the Current ENDCAP composed of 3 RPC stations covering 1.1 <η< 1.6 → Trigger requiring 3/3

Trigger efficiency of the muon system is low due to

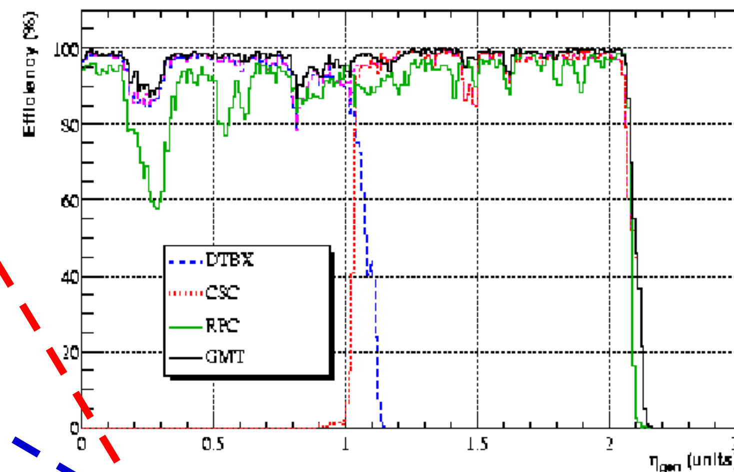
- Absence of 4-th stations (PHASE I)

Add a layer → Trigger requiring 3/4

- Absence of RPCs in 1.6 <η< 2.4 triggers. (PHASE II)



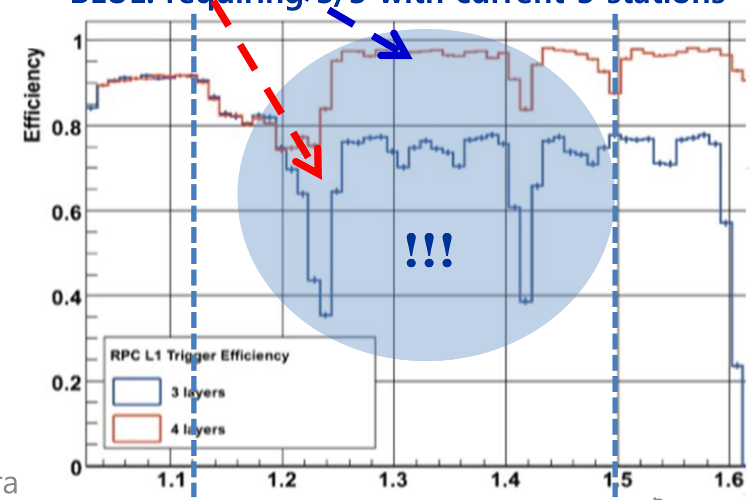
Global Muon Trigger efficiency proposed in the TDR LHCC-97-32



RPC Trigger Efficiencies

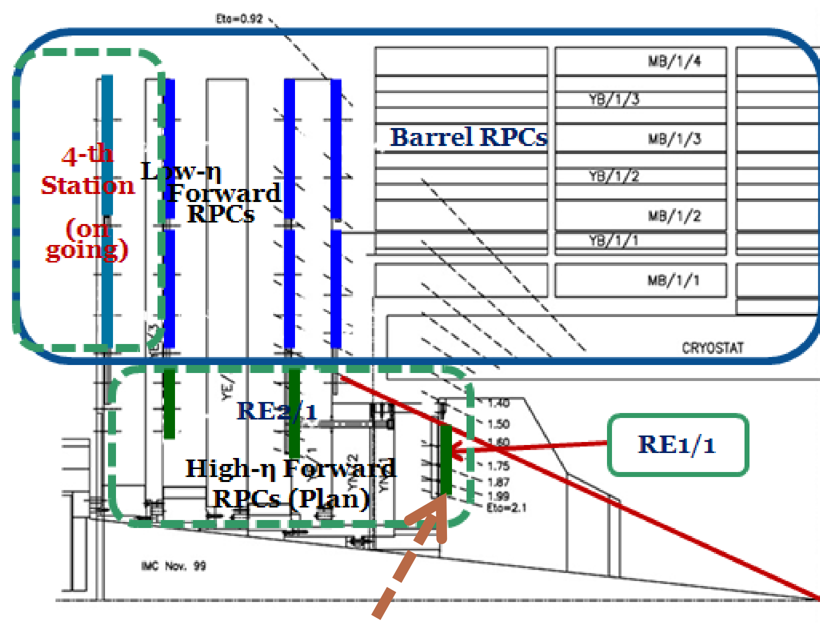
RED: requiring 3/4 with a new 4th station

BLUE: requiring 3/3 with current 3 stations



3. PHASE II upscope: high-η trigger (RPCs & GEM)

(Many R&Ds and proposals)



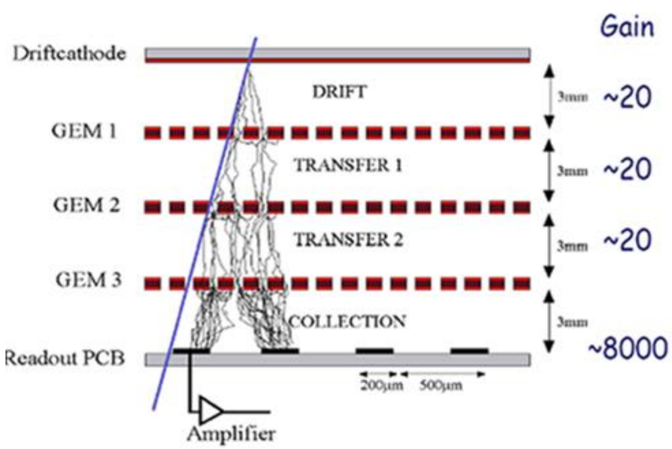
1. GEM trackers at RE1/1 → GE1/1

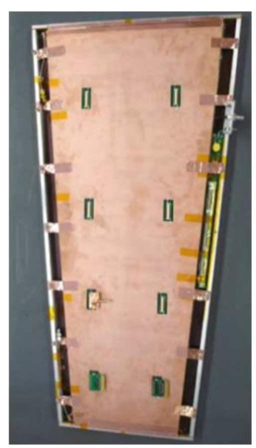
- High priority
- RPCs closest to the collision vertex with presence of strong magnetic fields.
- Expect effective rejection of the beam backgrounds (γ, n, π) of 1 ~ 2 kHz/cm^2 at L = 10^{35} cm^{-2} s^{-1}

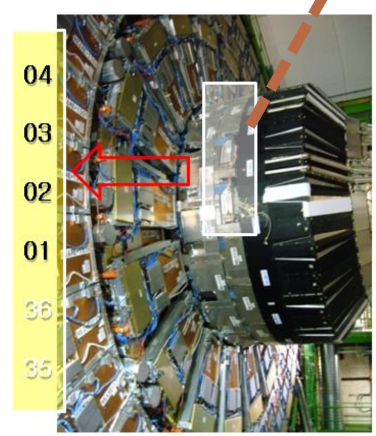
Basic structure

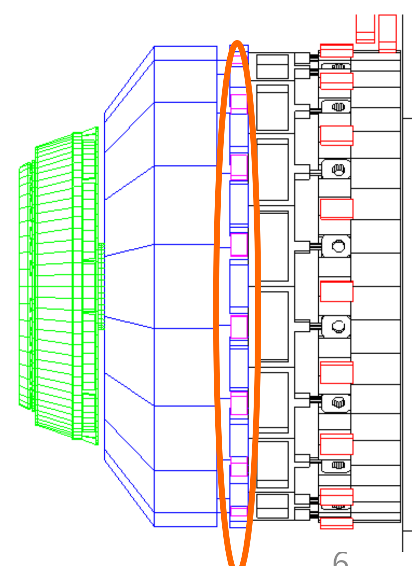
2 ~ 3 GEM plates : for the amplification of X-ray signals

Two dim. microstrips (~ 100 ㎛ spacing : to pickup the avalanche images)









2. Multi-gap RPCs (HPL or glass) for RE2/1, RE3/1 and RE4/1

❖ **Direction → Smaller detector charges**

a) To reduce aging at high rate background

b) To enhance rate capability

❖ **Lower avalanche charge**

- Rate capability ~ $1/\rho$
- Smaller q_e → higher rate capability

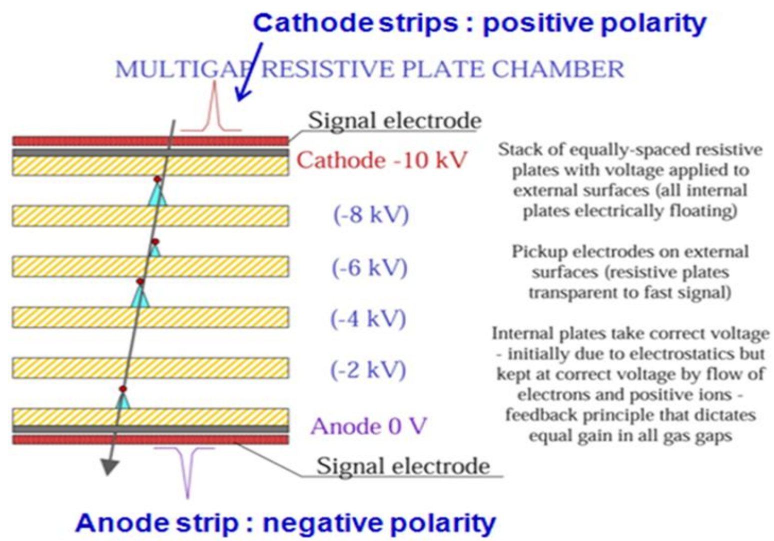
❖ **Typical glass 6 or 8-gap RPCs (timing RPCs)**

✓ $q_e < 1$ pC

✓ $\rho = 10^{12} \sim 10^{13}$ Ωcm for normal glass

= ~10^{10} Ωcm (ceramic & low res. glass)

Thin-glass MRPC (timing RPCs)



❖ **But we need Panel-shape RPCs for future CMS muon triggers in CMS/LHC.**

Expected particle rates at $L = 10^{35}$ s^{-1} cm^{-2}

✓ At RE1/1 (nearest in 1.6<η<2.4) , N ~ 1 kHz cm^{-2}

✓ At RE2/1, RE3/1 and RE4/1 (others in 1.6<η<2.4), N < 300 Hz cm^{-2}

1) 4-gap normal-glass RPCs (rate capability ~ 1 kHz cm^{-2})

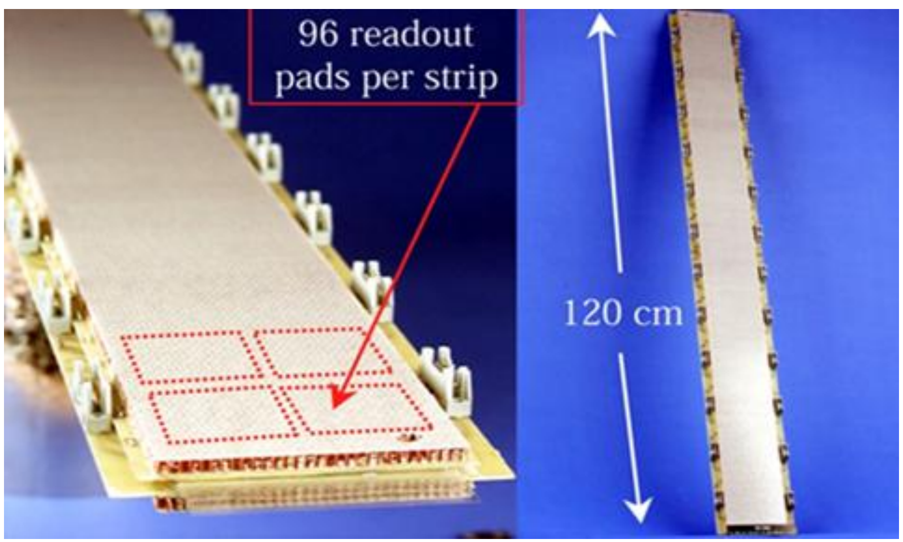
2) 8-gap low-resistive-glass RPCs (rate capability > 5 kHz cm^{-2})

3) 4-gap HPL RPCs (rate capability > 5 kHz cm^{-2})

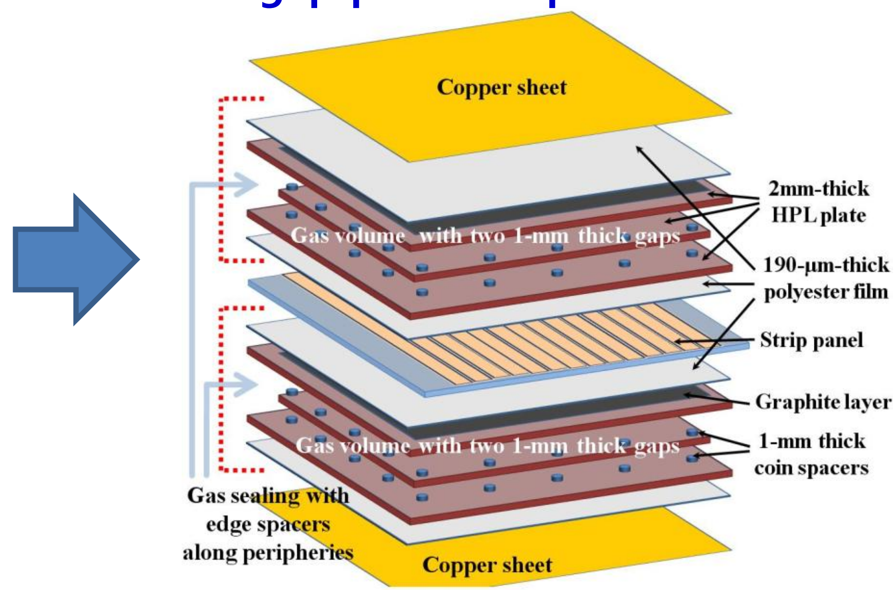
Korea University proposed 4-gap RPCs

- **4-gap HPL RPCs**
  - ✓ Expected rate capability N > 5.0 kHz cm^{-2}
  - ✓ Aiming for **RE1/1**
  - ✓ Triggers only, no good information for positions
- **4-gap thin normal glass RPCs**
  - ✓ Expected rate capability N ~ 1.0 kHz cm^{-2}
  - ✓ Aiming for high-quality trigger for **RE2/1, RE3/1, and RE4/1**
  - ✓ Having partially tracking probability: position resolution ~ 2 mm
  - ✓ Cathode-strip readout → division of strip along η

Thin-glass 8-gap MRPC (ALICE timing RPCs)

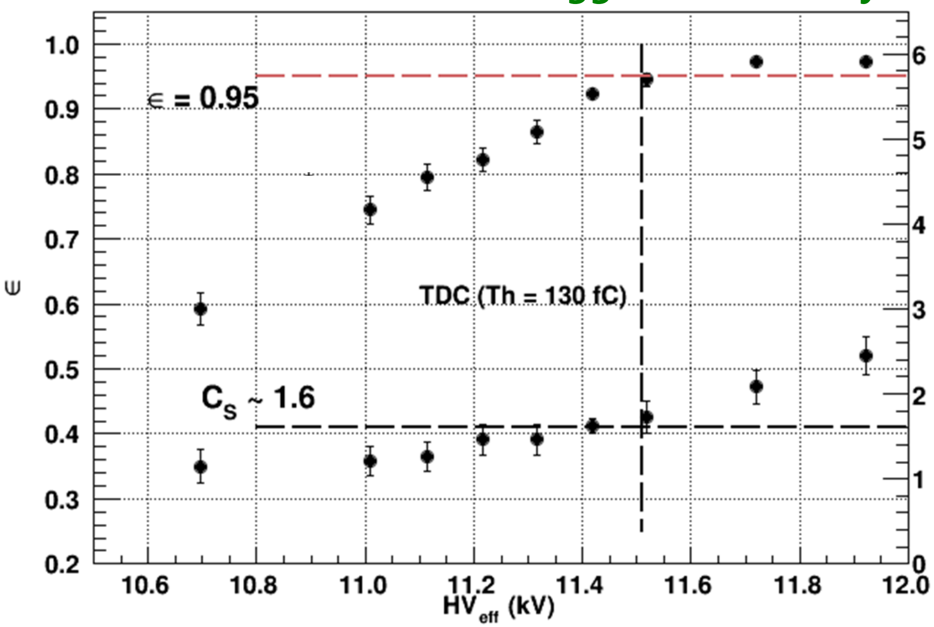


4-gap panel-shape MRPC for CMS

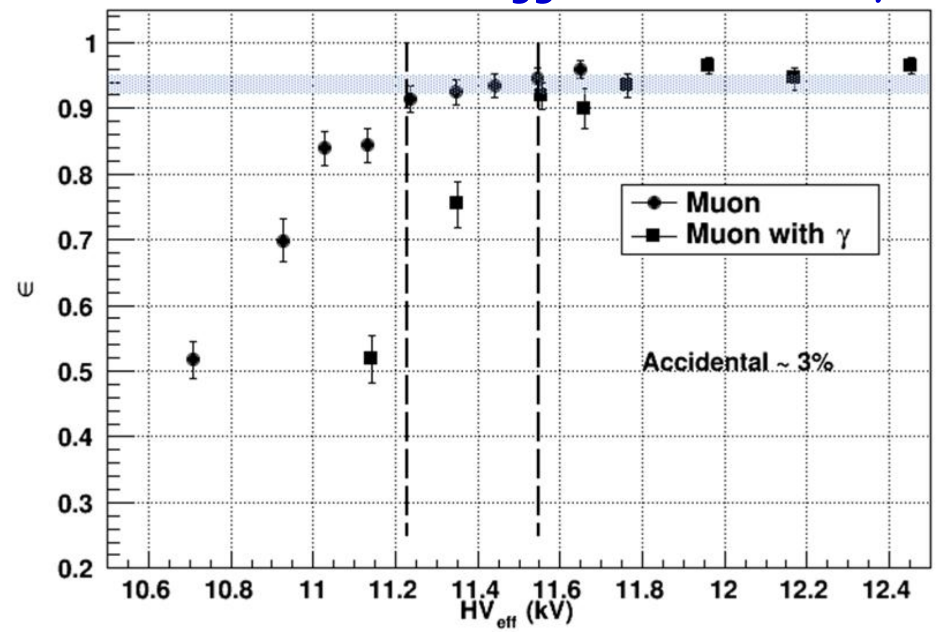


Rate capability study for a prototype 4-gap HPL RPC

Efficiencies of muons tagged horizontally

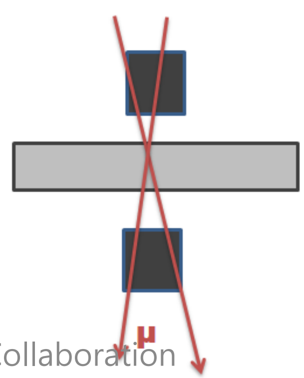


Efficiencies of muons tagged with intensive γ's

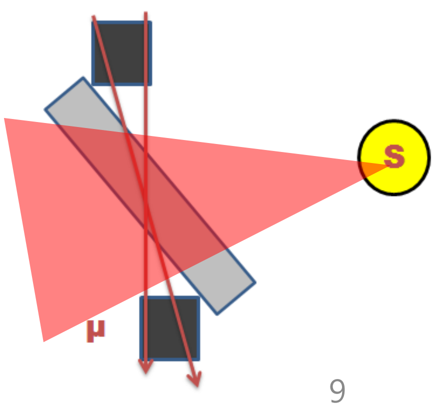


- Tested with 64-ch Multi-hit TDC
- Threshold = 195 mV (~130 fC in a CMS FEE)
- Gamma ray source: 150-mCi ^{137}Cs
- Test results
  - ✓ Muon efficiency plateau > 600 V
  - ✓ HV shifts ~ 400 V at N_γ ~3.0 kHz cm^{-2} with ρ = 5.0 x 10^{10} Ωcm
  - ✓ No degradation upto N_γ = 5.2 kHz cm^{-2}
  - ✓ **Expected rate capability N_γ > 5 kHz cm^{-2}**

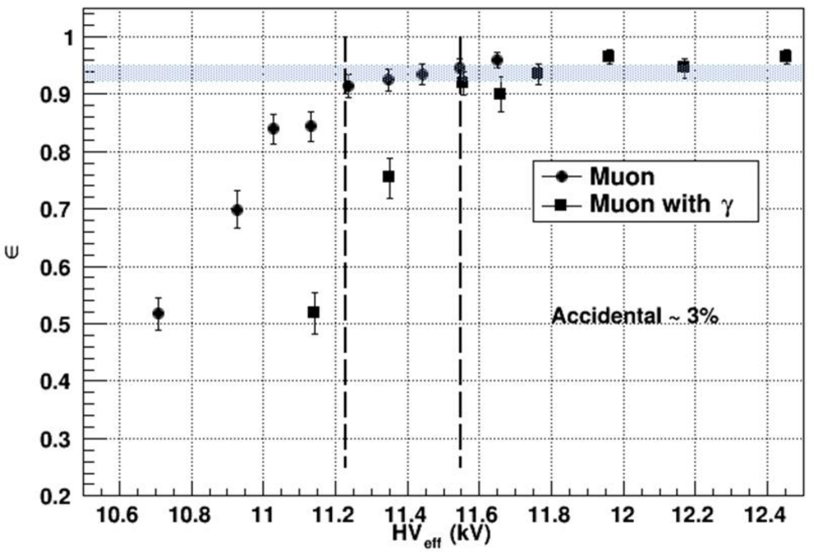
Horizontal muon tagging



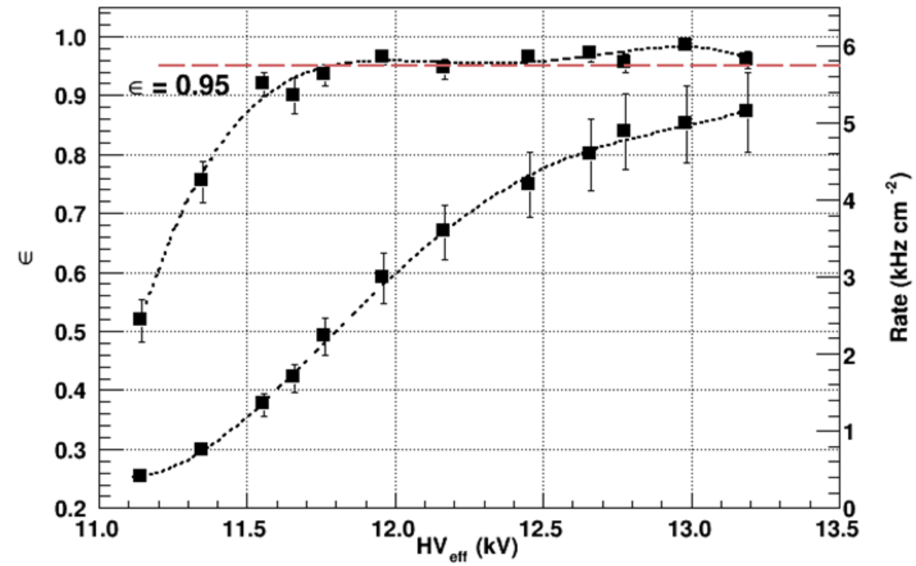
Muon tagging together with γ



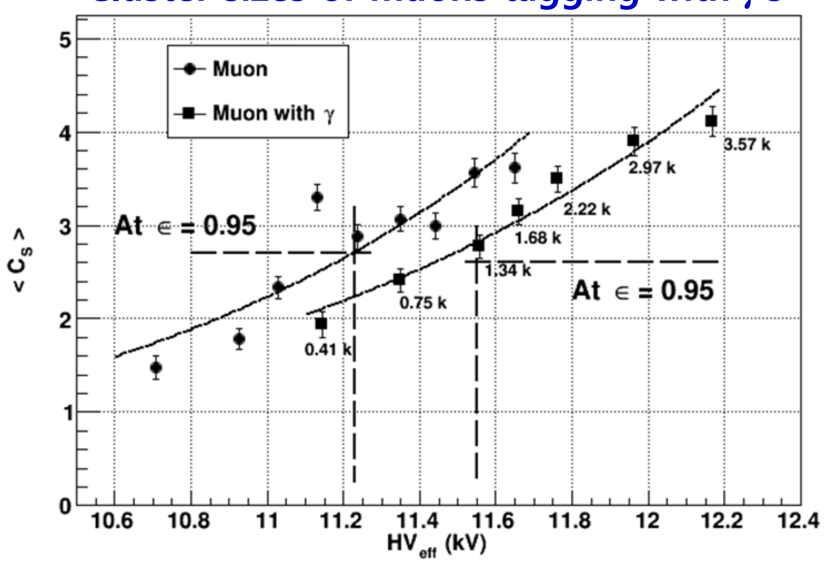
Efficiencies of muons tagging with γ's



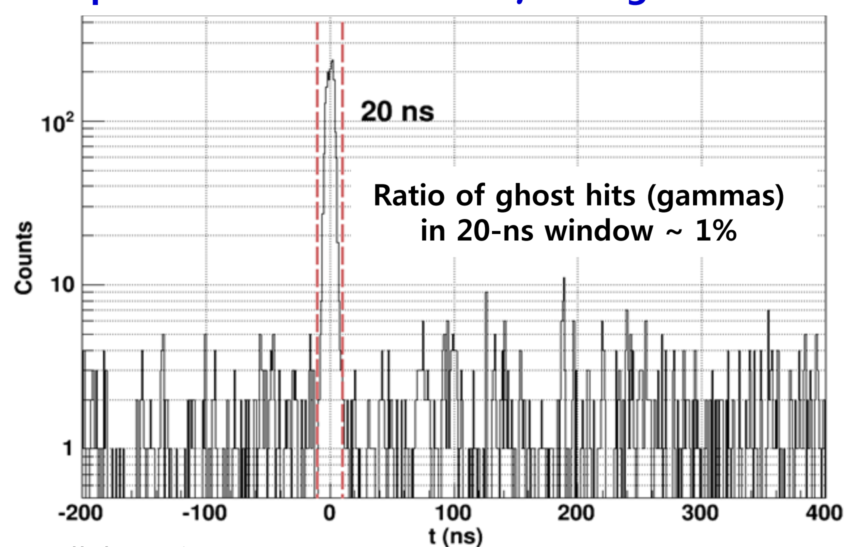
Efficiencies & Rate



Cluster sizes of muons tagging with γ's



Tagging muons with ε>0.95 with presence of 5 kHz cm^{-2} γ-background hits



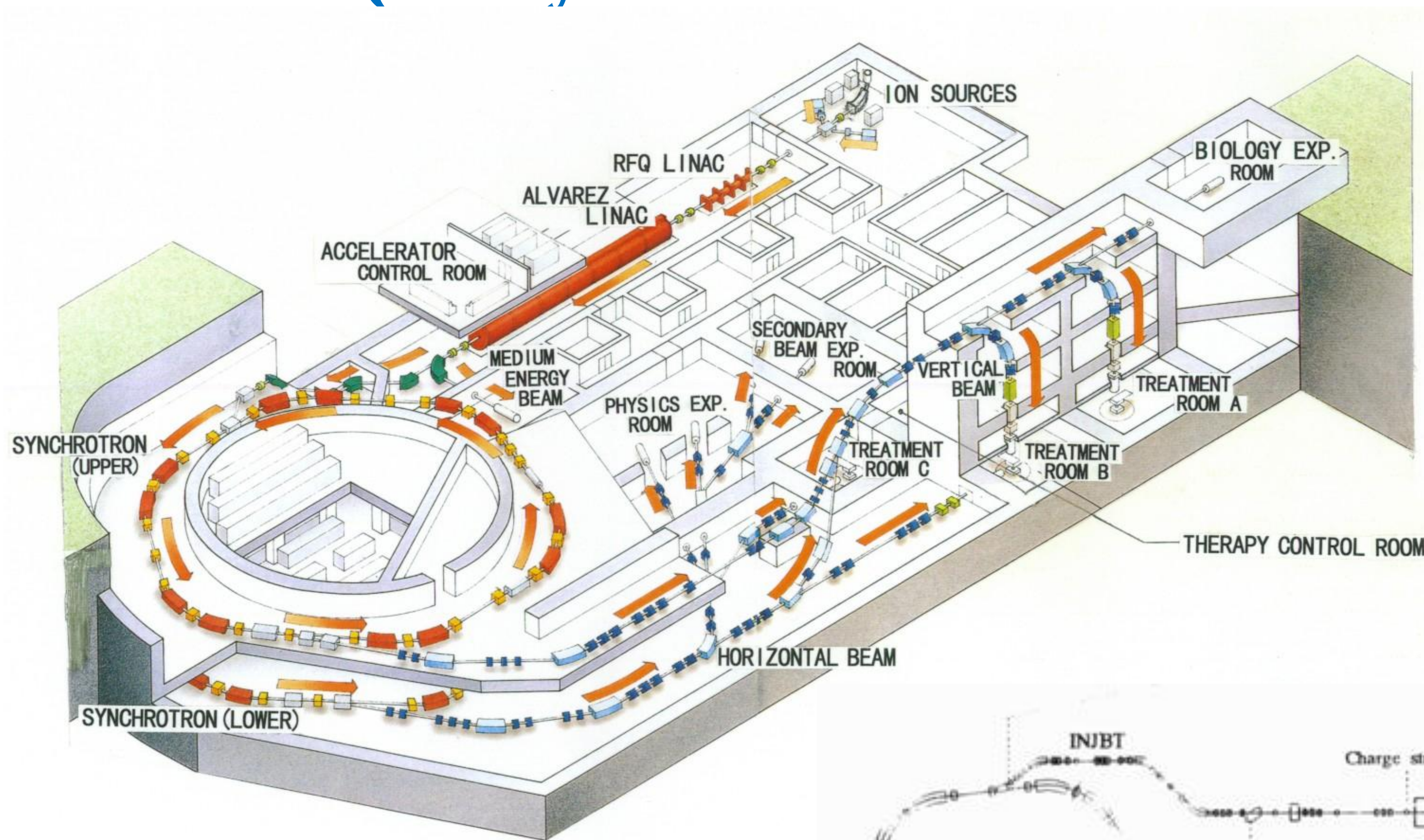
1. Introduction

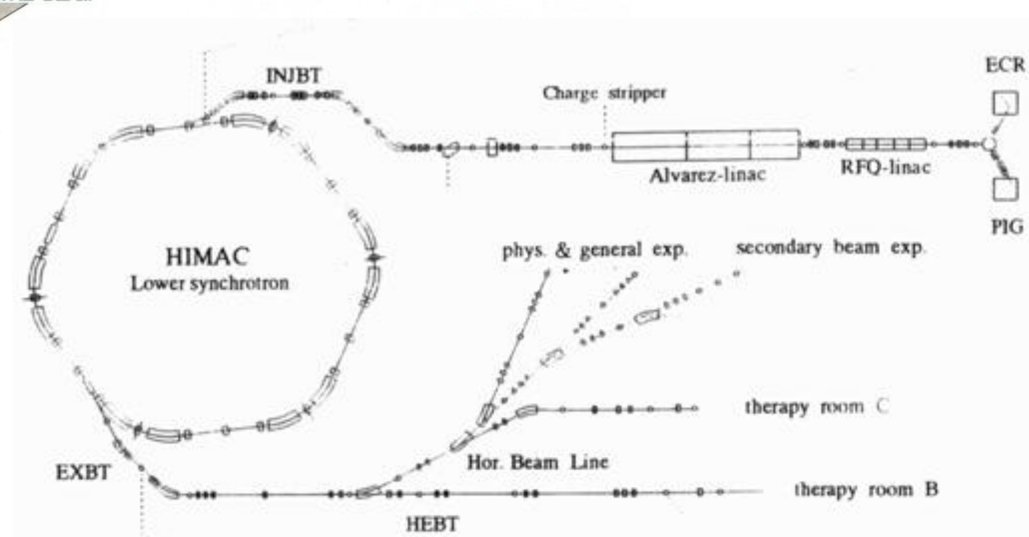
- **Motivation of research: fast & precision measurements for verification of the therapeutic hadron beam in particle therapy**
  - Proton beam (100 ~ 300 MeV)
  - Heavy-ion beam (~ 400 MeV)
- **Goal: development of fast detector system for therapeutic beams**
  - Scattered beams (passive, static)
  - Dynamic wobbled and pixel-type beams (dynamic)

  → Detection required for fast time-dependent dose measurements
- **Dose measurement in a 3-dimensional way**
  - Bragg peak → only one dimensional distribution for range
  - Precision measurement for the lateral dispersion
- **Simultaneous measurement of dose with a multilayer detector**

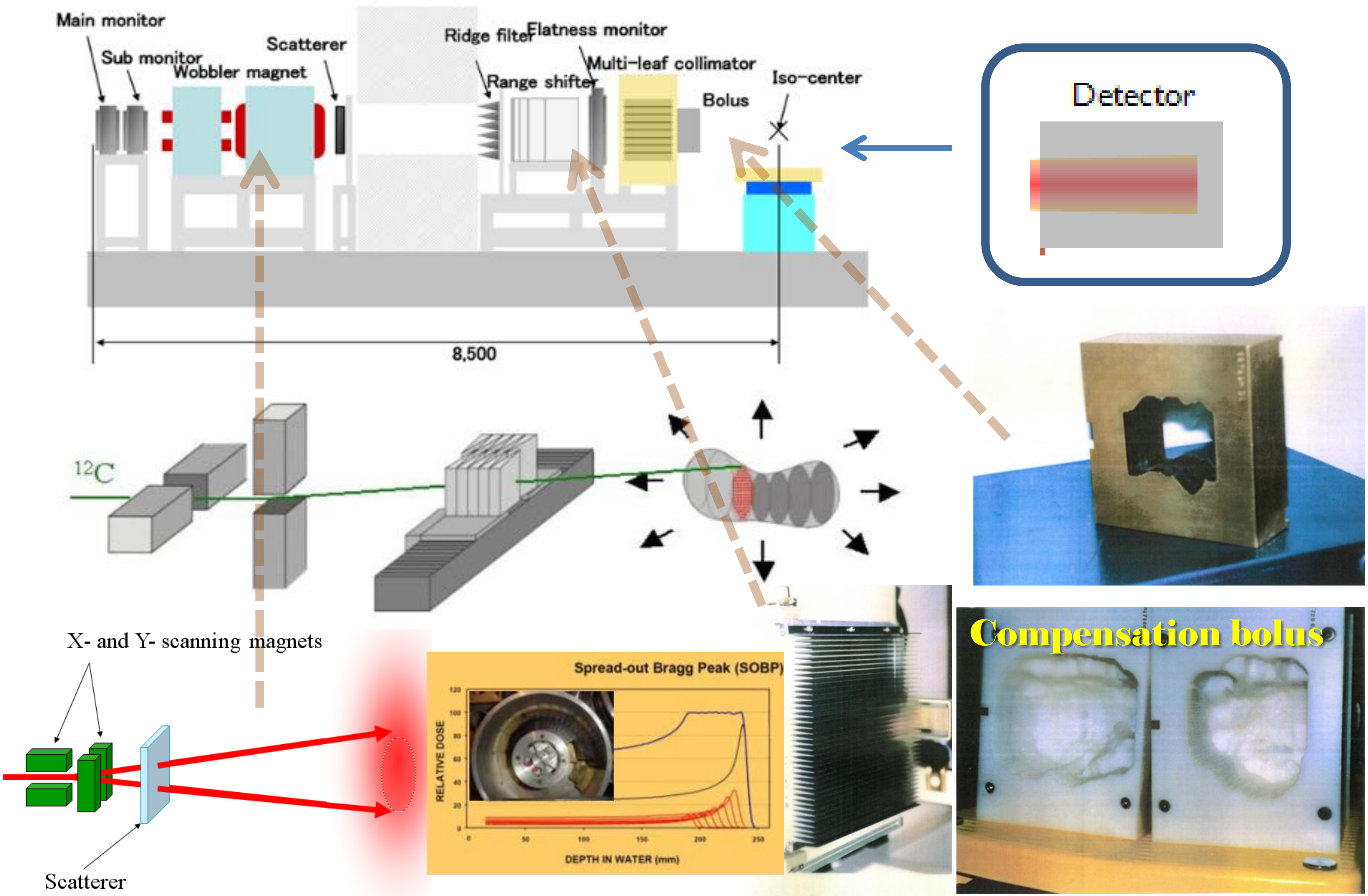
  → Enable to reduce scan times and labor in the dose-verification procedure

HIMAC (Heavy Ion Medical Accelerator Facility)





HIMAC (Heavy Ion Medical Accelerator Facility)

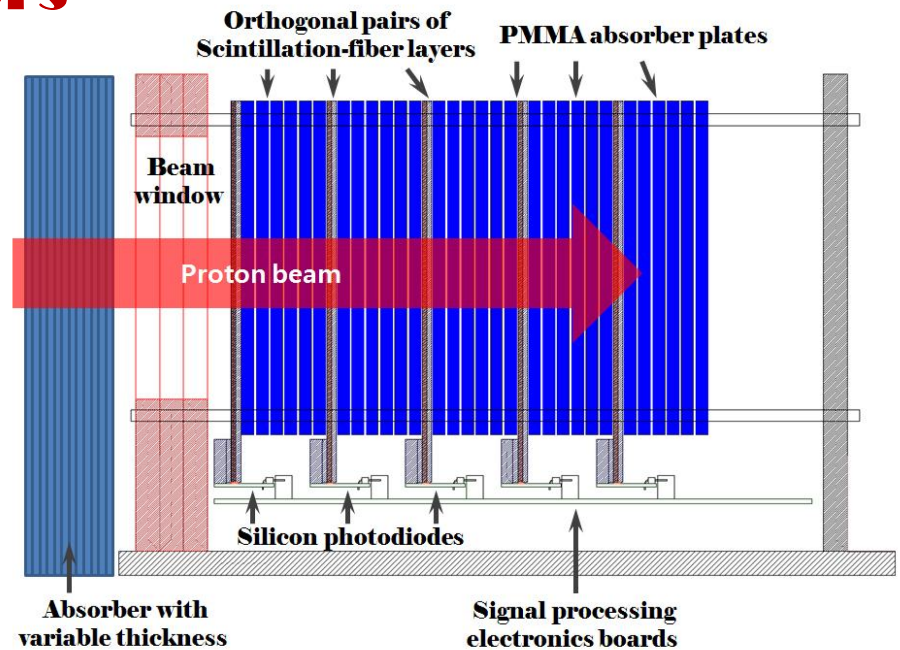


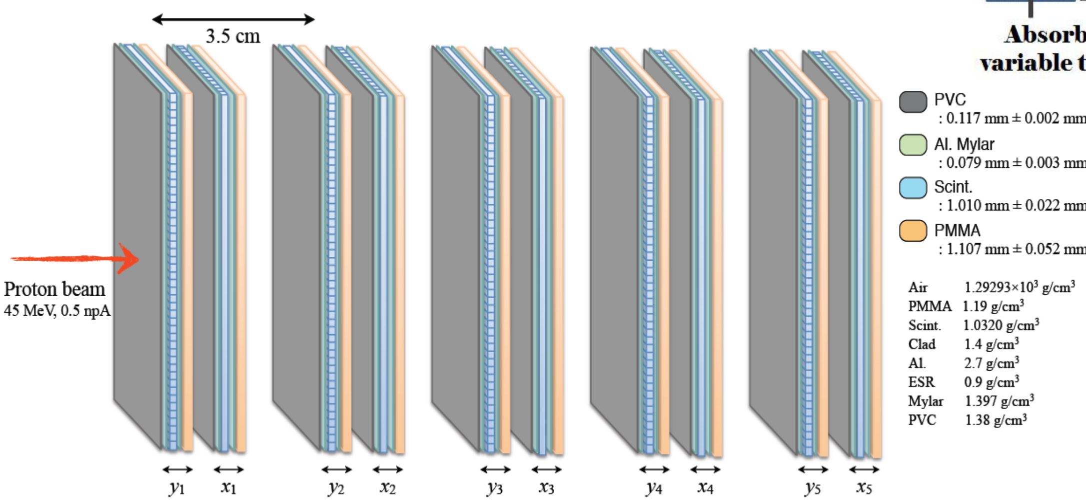
1. Scintillation-fiber detectors

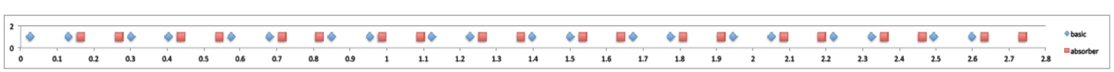
Detector composed of 10 fiber layers

Performed a beam test with 43-MeV protons with no PMMA absorbers

→ Measured at depths ranging from 0.301 to 1.810 g cm^{-2}





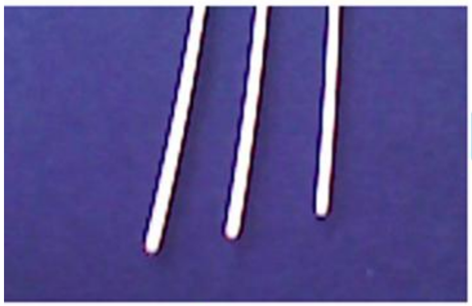


each bin size : 0.1042 g/cm^2
absorber : 0.1107 cm-thick PMMA + 0.0065 cm-thick ESR = 0.0376 g/cm^2

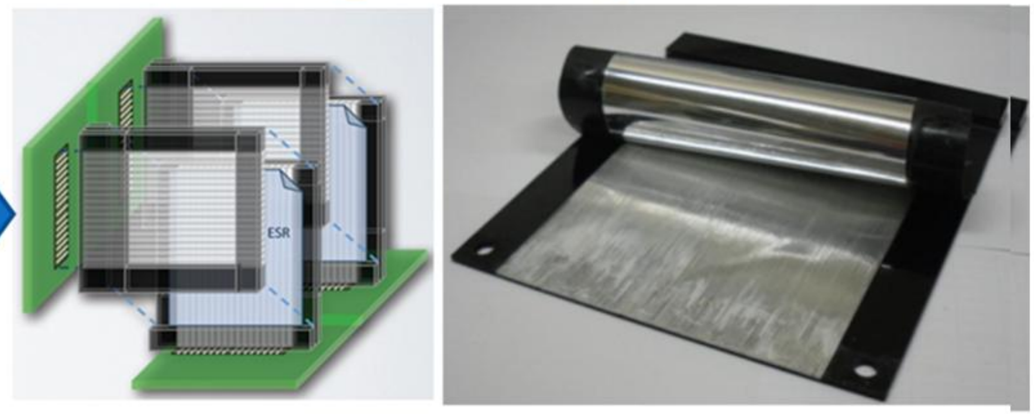
Bicron BCF-60 fibers

- 1.0-mm thick squared and double-clad
- Light yield ~ 7000 /MeV
- Maximum yield at 530 nm

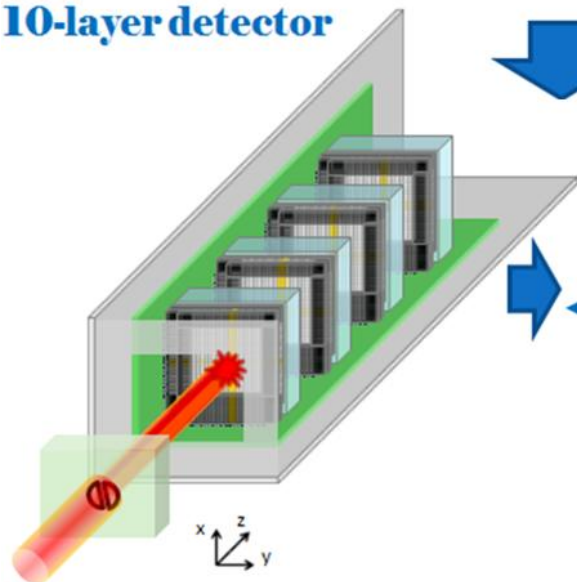
Scintillation fibers

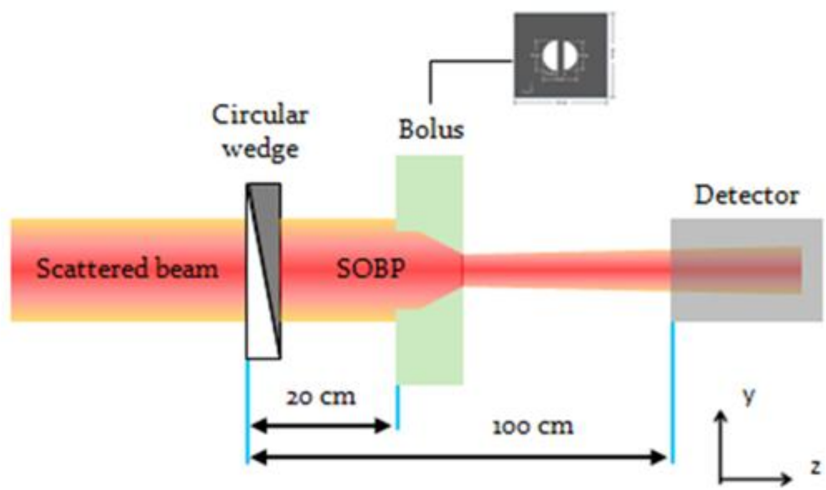


Two single detector layers



10-layer detector



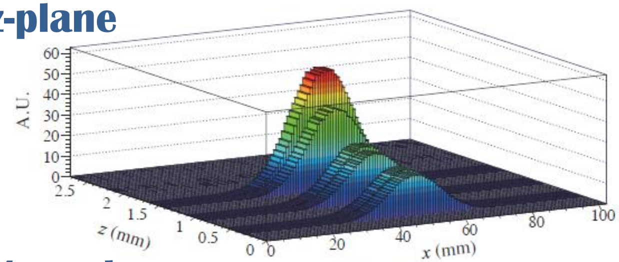


Tests with MC50 proton beams at KIRAMS

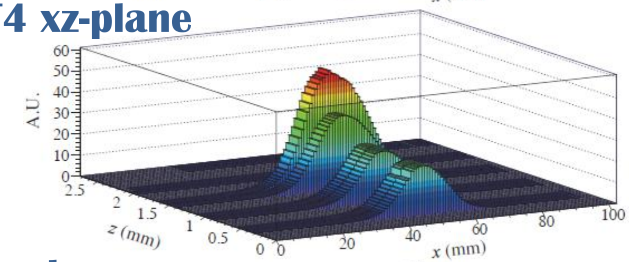
Detector-response for 10 s at depths from 0.301 to 1.810 g cm^{-2} for a 1-nA beam

(After the calibration using a reference beam)

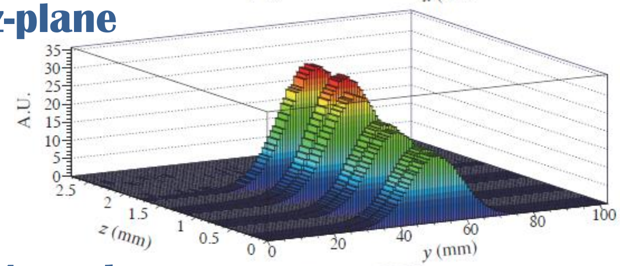
Data xz-plane



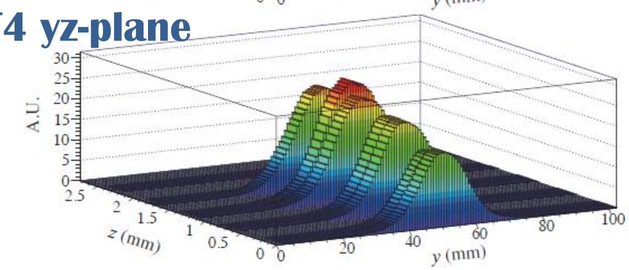
GEANT4 xz-plane



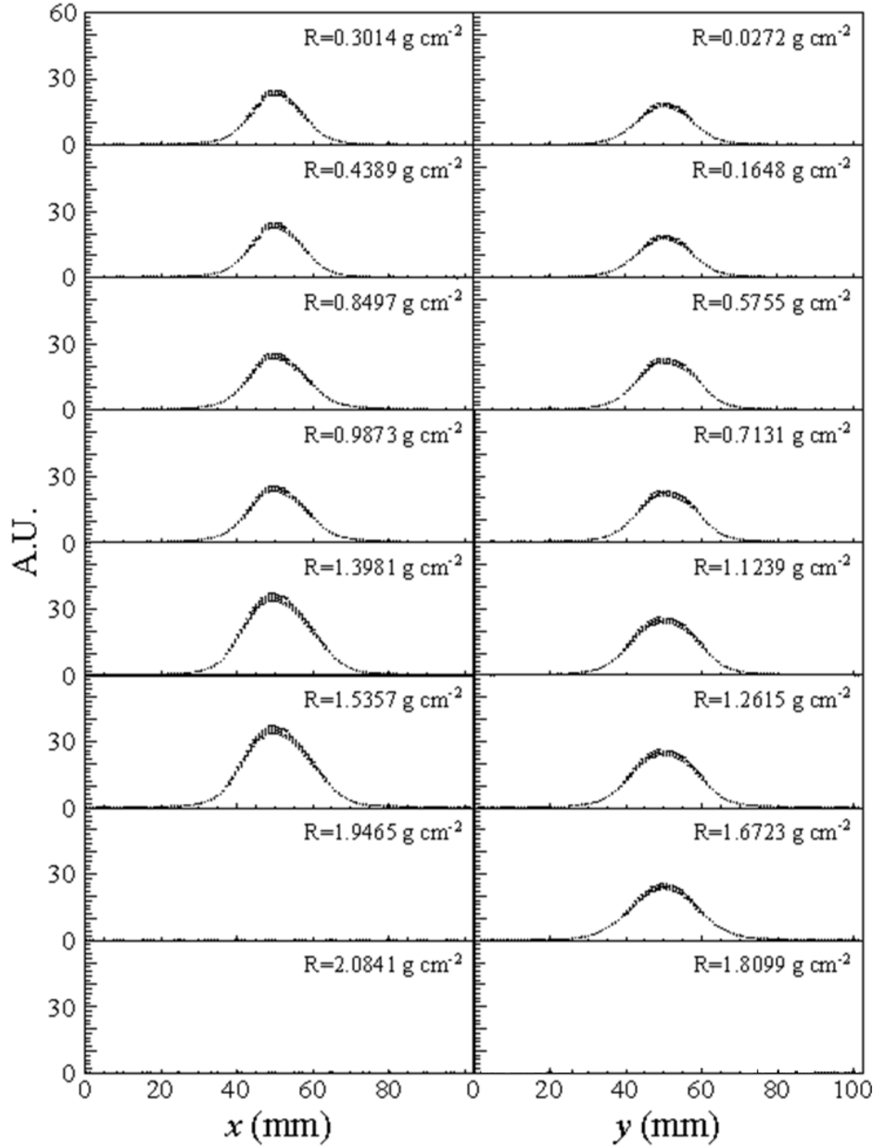
Data yz-plane



GEANT4 yz-plane



Channel fluctuation = 0.9 ~ 1.2% in sigma



2. Thin Ionization Gas Detectors

- Single-GEM loaded detector
- Plane detector without a GEM foil

❖ **Gaseous detector → can avoid the difficulty in calibration due to the severe nonlinearity to ELOSS**

→ Measured data directly reflects the doses (*i.e.*, *dE/dx*)

→ More reliable for heavy-ion measurements

❖ **Thin detector thickness compared to wire chambers**

→ Advantageous for building multilayer detectors

❖ **Radiation hardness**

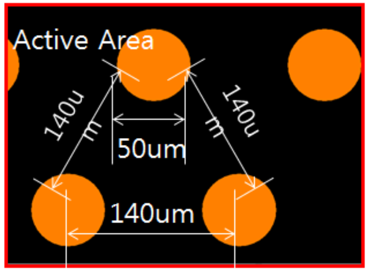
→ Harder compared to scintillator materials

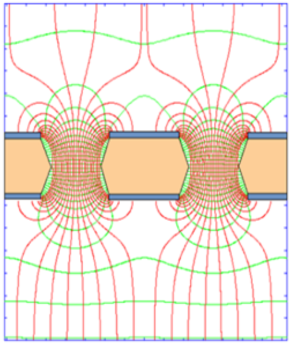
❖ **Use GEM: the detector gain can be adjusted.**

→ Large dynamic range for measureable beams (10 pA ~ 10 nA)

❖ **GEM: a thin copper coated electrode with a 2d hole-pattern (made in Korea)**

- Thickness of Kapton foils = 50 μm
- Hole diameter ~ 50 μm
- 2d-pitch = 140 μm





Single-GEM detector for a dose-measurement detector

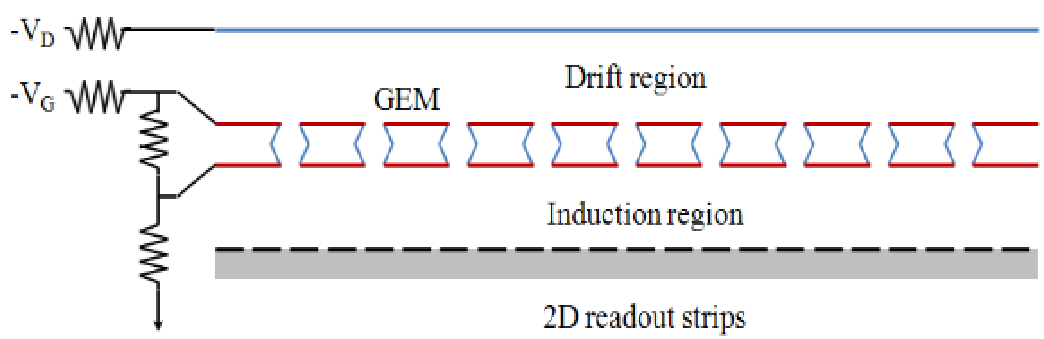
Propose for both proton and heavy-ion beam

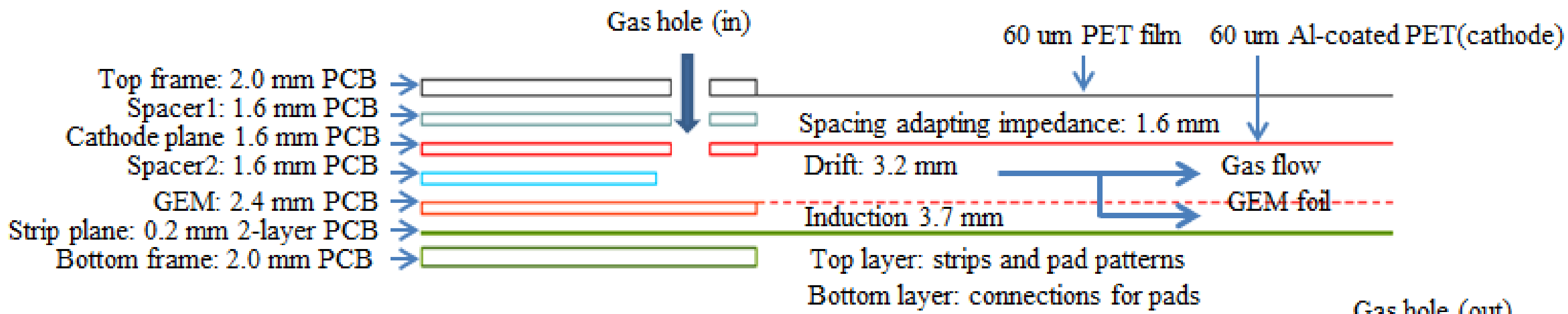
- ✓ Beam-profile detectors (thin Al coated PET for the cathode)
- ✓ Unit detectors for dose-measurement system
  (cathode printed on 1.6-mm thick PCB to allow energy loss)

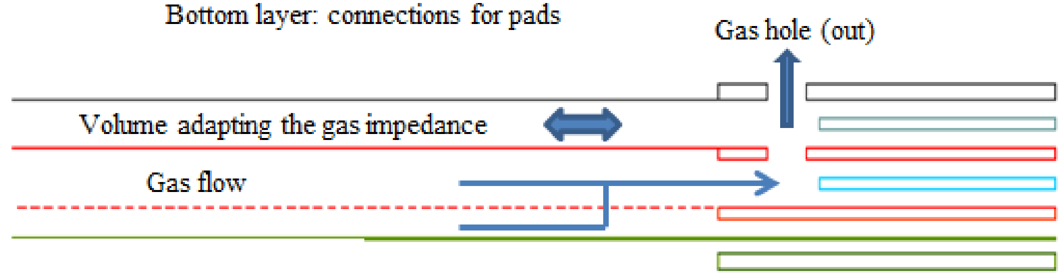
~ A 10 layer detector system (final goal)

- ➢ Active area = **160.0 x 160.0 mm²**
- ➢ Multilayer PCB with FR4 (epoxy glass)
- ➢ GEM size (measurable field) = **160 x 160 mm²**
- ➢ Capacitance = 1.59×10^{-8} F
- ➢ **ΔV_{GEM} = 400 V**
  2.5 kV/cm at drift region
  3.1 kV/cm at induction region
- ➢ Separate distributions for *x* & *y*
- ➢ 128 channel for each direction
- ➢ Pitch= **1.25 mm**

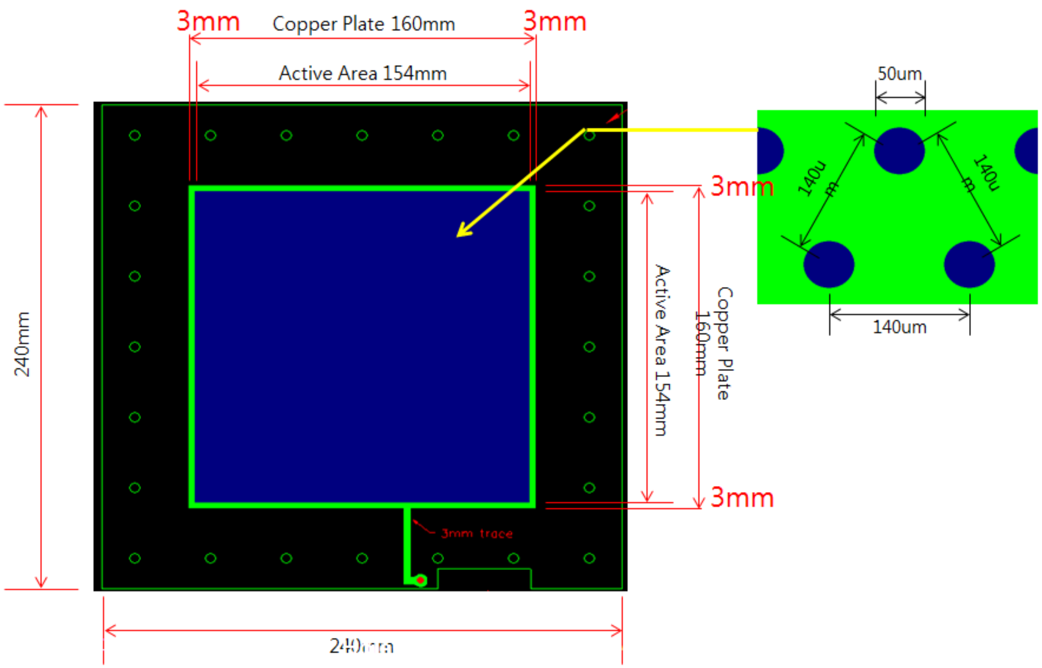
Schematics of a single-GEM detector

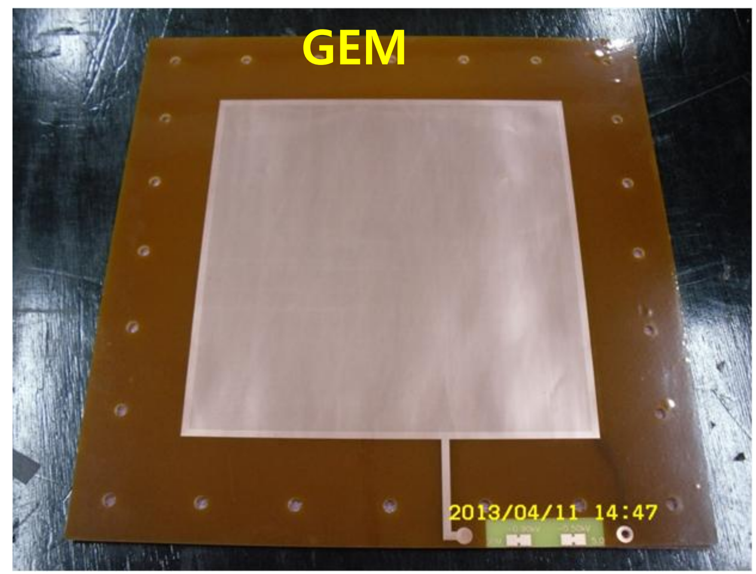






※ 1616 GEM Lay-out (for Korea Unv.)





Signal plane (0.2 mm PCB)

- ✓ Strips and pad patterns on upper layer
- ✓ Connection lines for pads on bottom

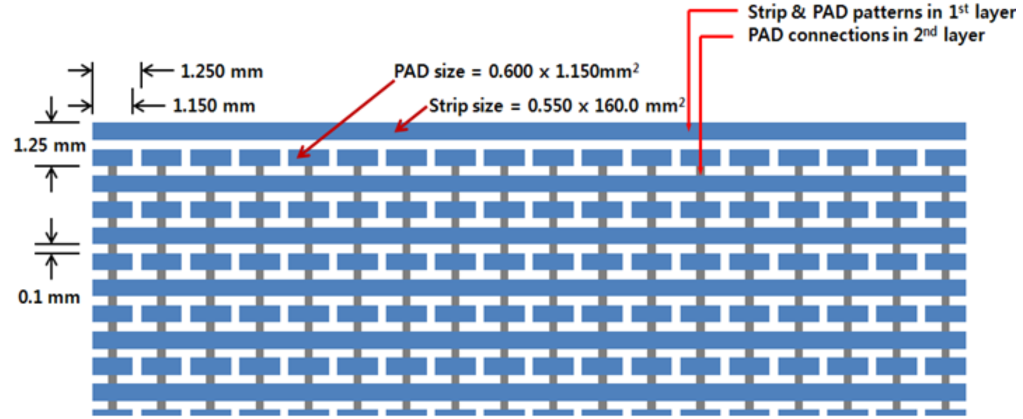
Signal readout:

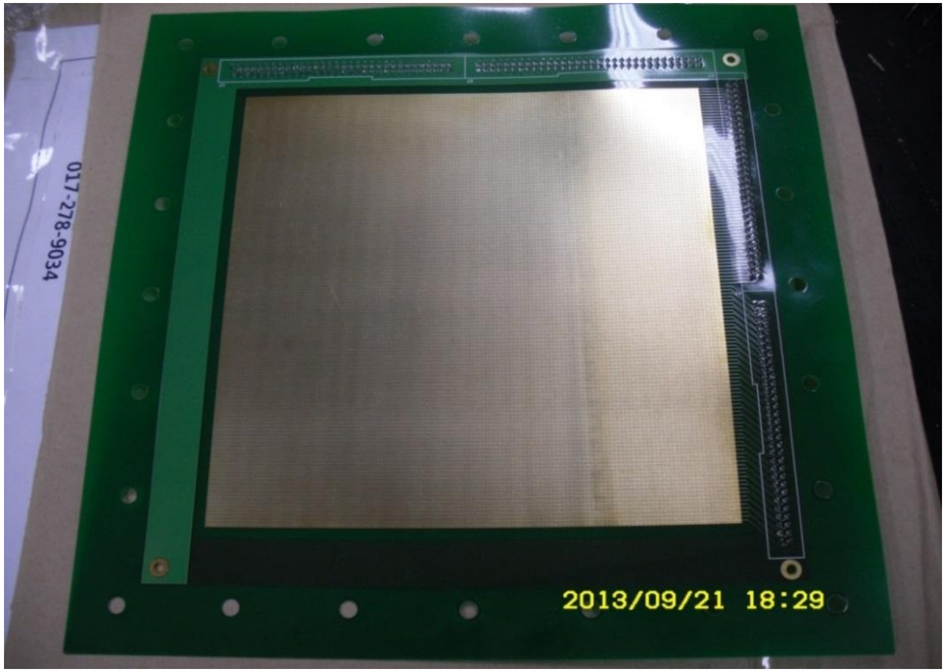
- ✓ Four 64-pin ribbon connectors and two twist-pair cables with 1.25-mm pitches
- ✓ Maximum channel sensitivity:
  5.2 ~ 384 nA/ch
- ✓ Charge induced at pad or strip fed into directly QDC chips (128 channels) in the signal processing board
- ✓ Data translation protocol: **USB3**
- ✓ Data bit transfer rate: **10 Mbps**
- ✓ Datum transfer rate: 8.7 ~ 35 kHz

  x and y distributions (128 x 128) produced every **28.6 μs** **(35 kHz)**

Gas mixture

- ✓ 70% Ar + 30% CO_2 (C30 gas)





Preliminary results for 45-MeV beams at KIRAMS

Single-GEM

loaded unit detector

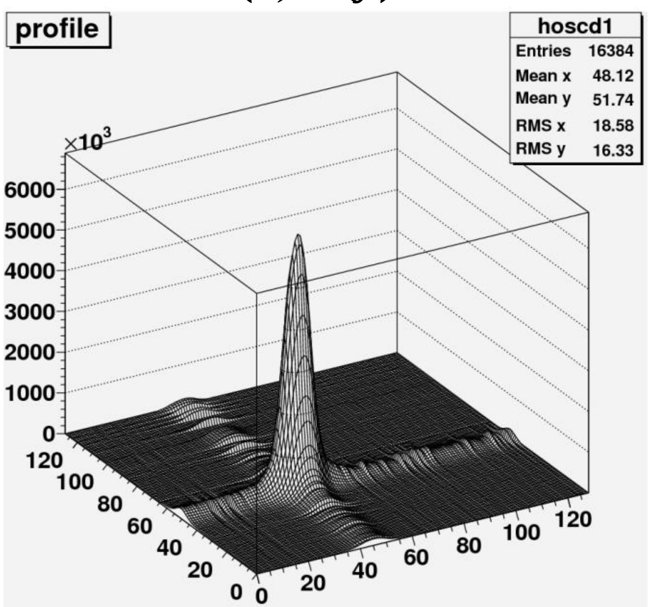
Thickness of induction

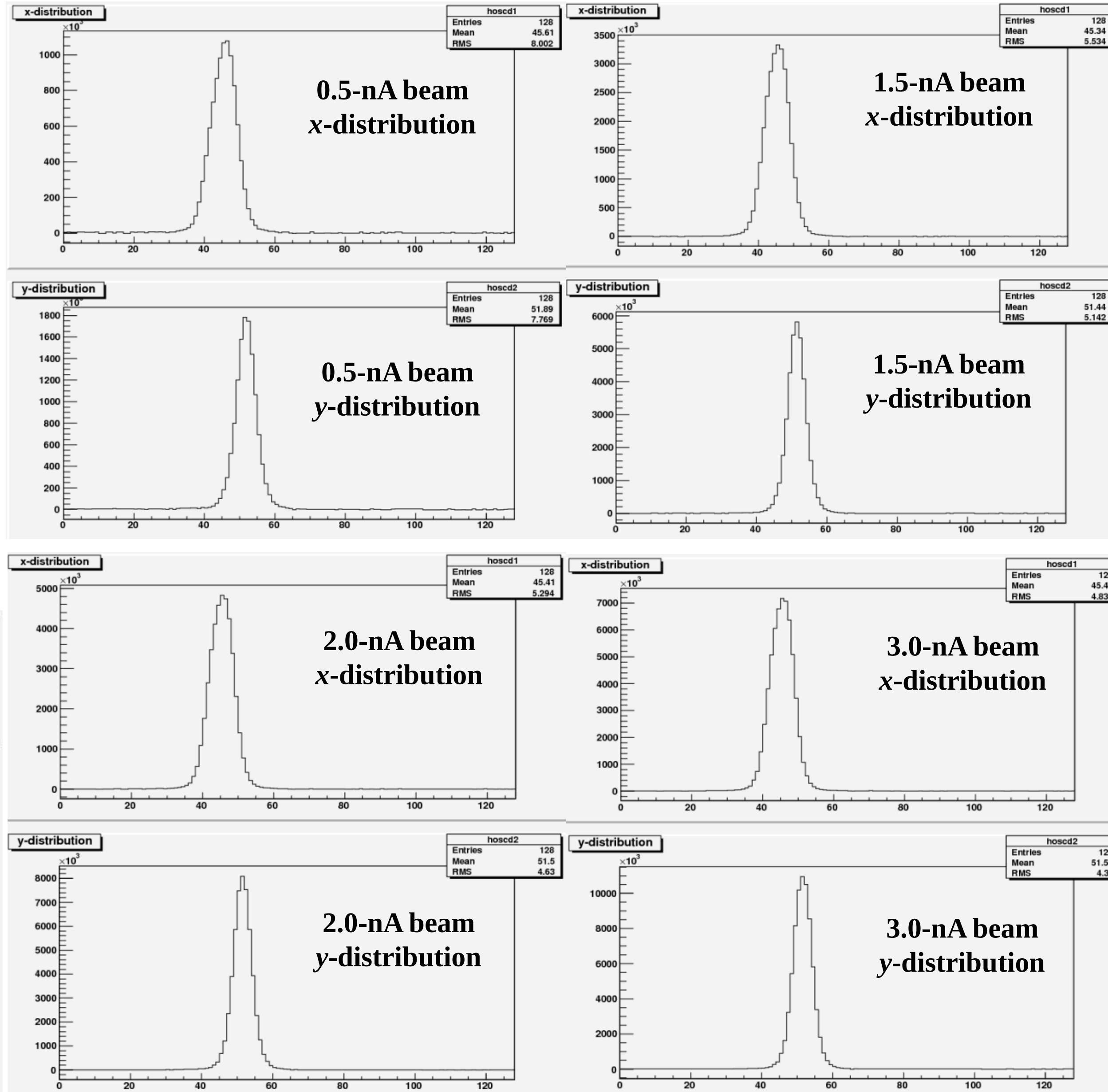
region = 3.8 mm

E_{ind} = 3.1 kV cm^{-1}

Pseudo 2-d image (1 s)

$[F(x) \bullet F(y)]^{1/2}$





Preliminary results for 45-MeV beams at KIRAMS

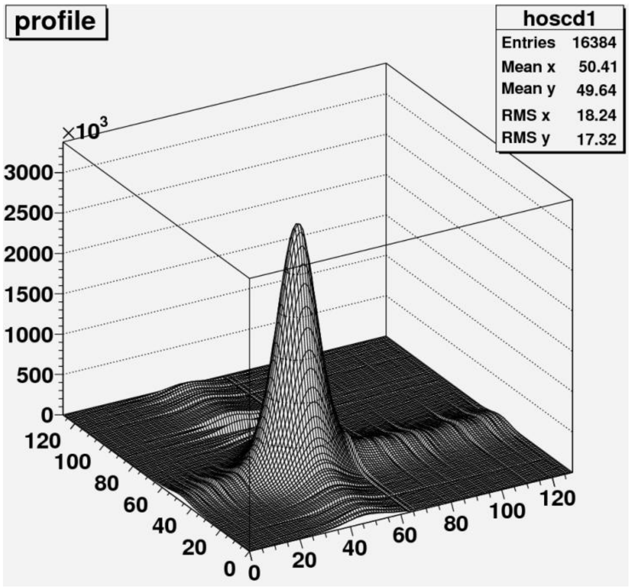
No-GEM loaded

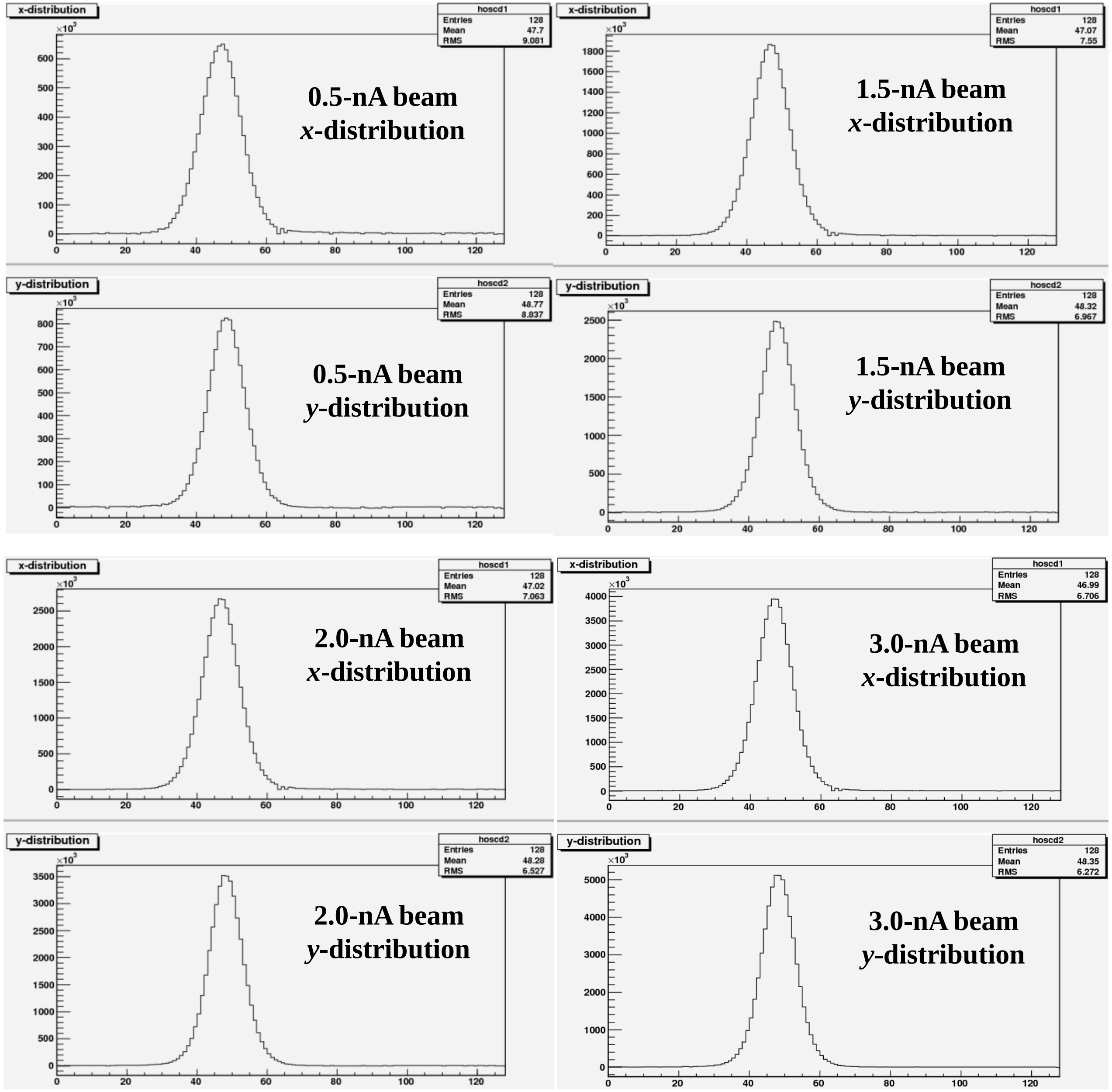
unit detector

Thickness of induction region = 3.3 mm

E_{ind} = 3.1 kV cm^{-1}

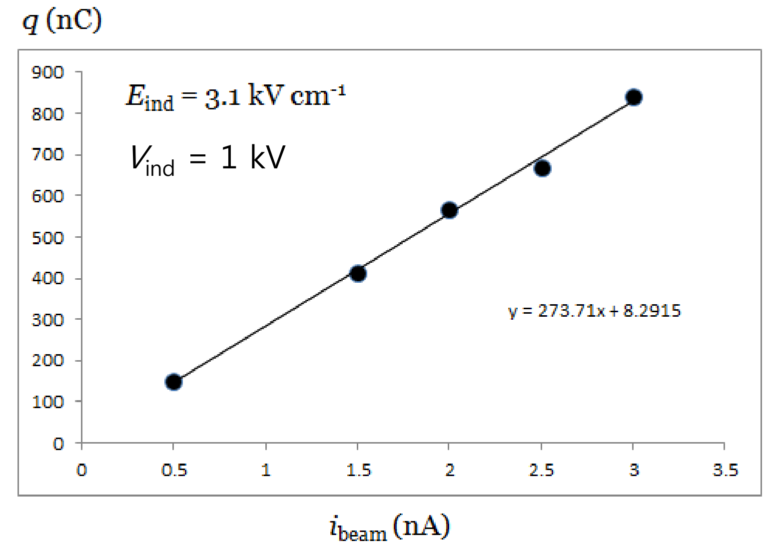
Pseudo 2-d image (1 s)
$[F(x) \bullet F(y)]^{1/2}$

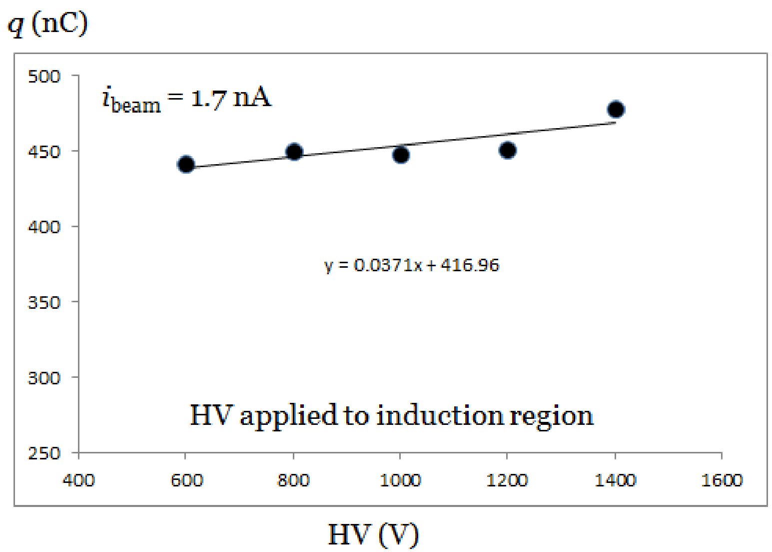




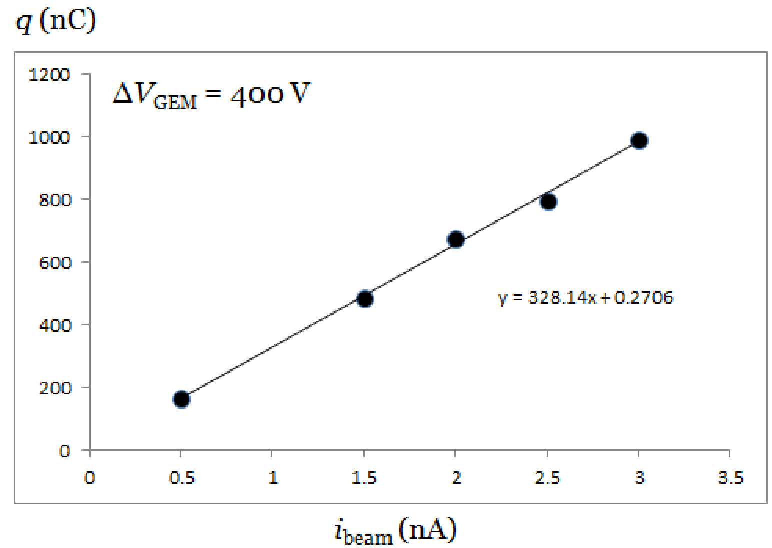
Induced charges for 1 s (accuracy for 43-MeV proton-beam currents ~ 5%)

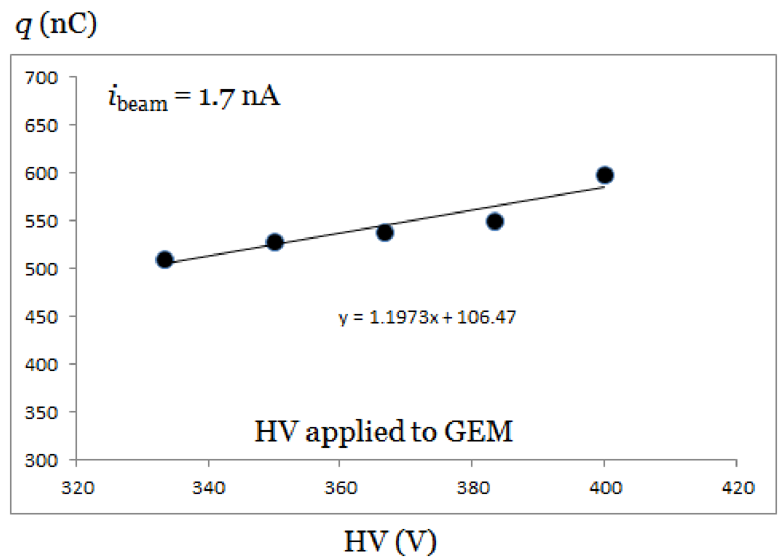
No-GEM loaded unit detector





Single-GEM loaded unit detector





3. Summary and Milestones

1) Scintillation-fiber technique in particle therapy

- ❖ Fast and quantitative dose data for therapeutic proton beams
  - ✓ 1% accuracy for spatial distributions (by Gaussian fits)
  - ✓ 3% fluctuation in time

  → Enables to track the beam dose with 250-Hz DAQ speed for dynamic beams.
- ❖ Inorganic scintillators like scintillation fibers

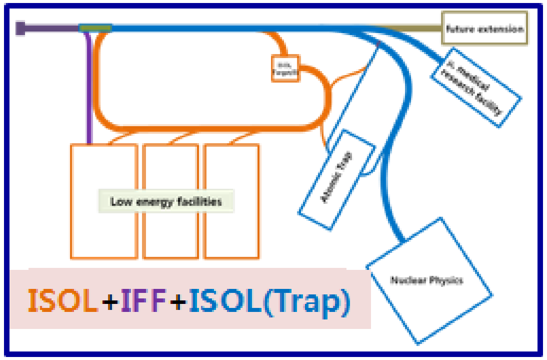
  → May NOT be adequate for measurement of heavy ions due to higher ELOSS (2^{nd} order nonlinear response would be significant)

2) GEM technique in particle therapy

- ❖ High statistical accuracy confirmed from the proton-beam test at KIRAMS
  - ✓ Designed faster electronics (35 kHz DAQ)
  - ✓ Confirmed the linear responses to beam current
  - ✓ Accuracy of measuring beam induced charges ~ 2% → Fairly good to
    - Beam measurements
    - Dose-verifications for both proton and heavy-ion beams,
- ❖ Linearity of the detector responses to ELOSS to be confirmed.
- ❖ Then, we build a 8 ~ 10-layer detector and test it with desirable dynamic-mode therapeutic protons (carbons if possible).

1. Introduction

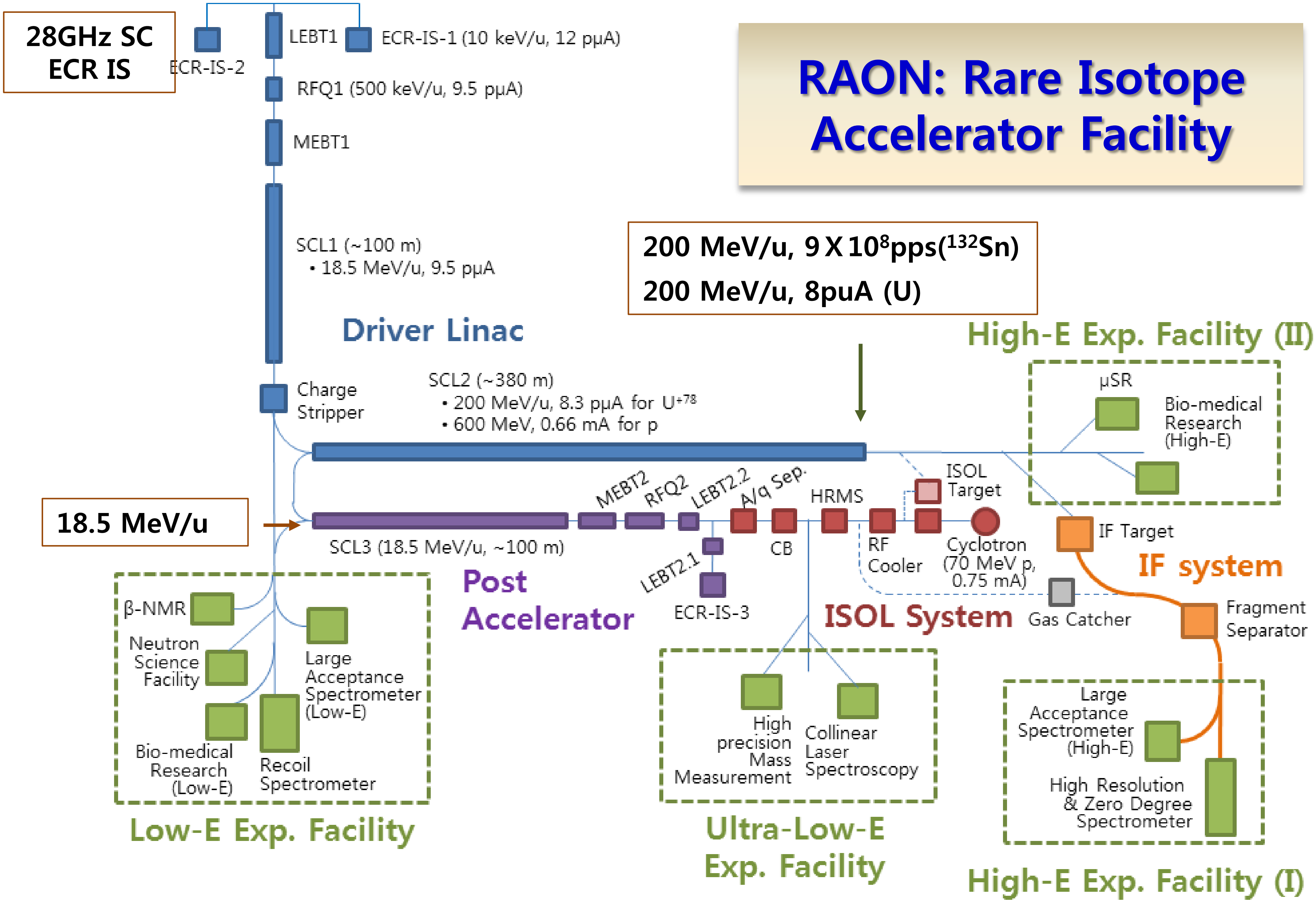
RAON: Rare Isotope Accelerator Facility



- Nuclear Physics
  - Exotic nuclei near the neutron drip line
  - Super-Heavy Elements (SHE)
  - Equation-of-state (EoS) of nuclear matter
- Nuclear Astrophysics
  - Origin of nuclei
  - Paths of nucleosynthesis
  - Neutron stars and supernovae
- Atomic physics
  - Limits of nuclear existence
  - Fundamental conservation law
- Nuclear data using fast neutrons
  - Basic data for future nuclear energy
  - Radioactive waste transmutation
- Material science
  - Production & Characterization of new materials
  - Dynamic image in nm scale
- Medical and Bio sciences
  - Advanced therapy technology
  - Mutation of DNA

RAON user community

RAON: Rare Isotope Accelerator Facility



2. LAMPS at RAON

- Large Acceptance Multi-Purpose Spectrometer to maximize the use of nuclear physics researches for neutron-rich nuclei
  - **Main purpose for Symmetry-Energy research**

    Understanding astronomical phenomena in neutron stars, black holes, and super novae by the EOS of nuclear matter at high density
  - **Pygmy Dipole & Giant Dipole Resonances**
  - **Neutron halos and exotic nuclei lying near neutron drip lines**

2. Conceptual designs of LAMPS

High-energy experiment (250 AMeV)

- ✓ Solenoid spectrometer equipped with a 3π-Sr TPC
- ✓ Dipole spectrometer with a focal plane detector system
- ✓ Large acceptance of neutron detectors via TOF measurement

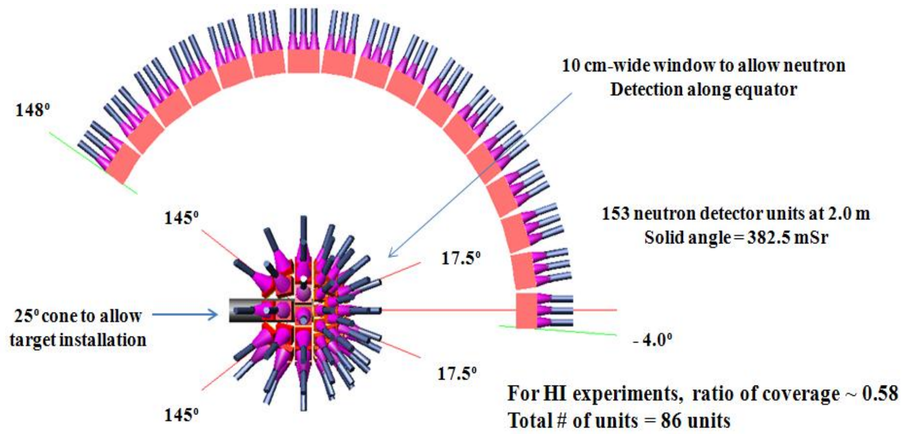
Low-energy experiment (< 20 AMeV)

- ✓ Vacuum system equipped with Si-CsI detectors
- ✓ Large acceptance of neutron detectors via TOF measurement

LAMPS: design for low-energy experiment

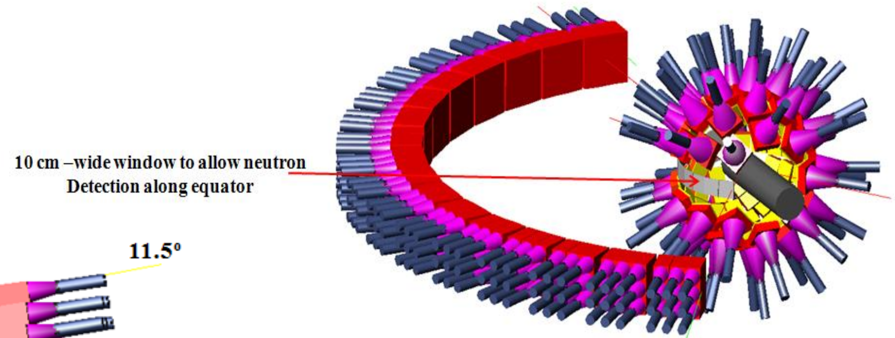
Vacuum chamber

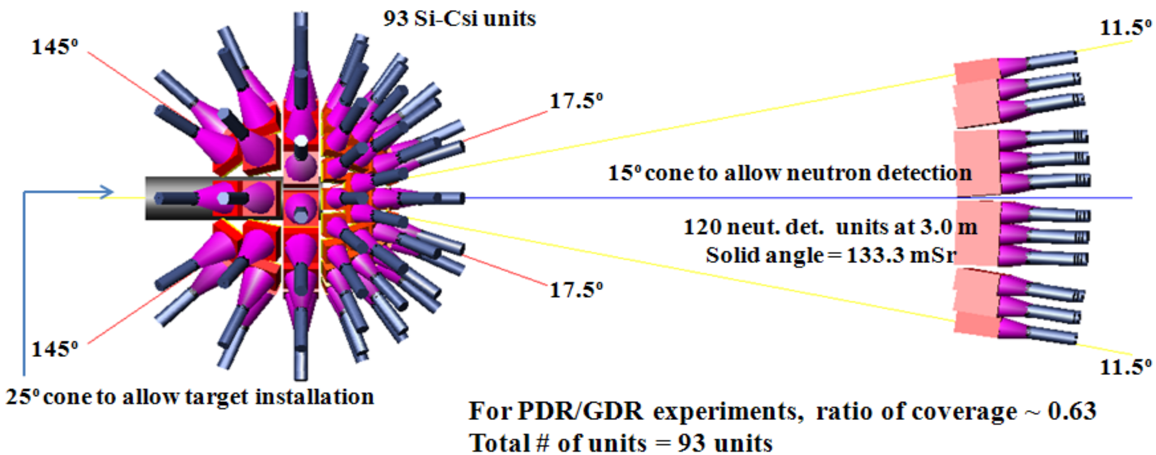
- **Si-CsI array (charged particles & γ)**
  - ✓ $\Delta E/E \sim 10^{-2}$
  - ✓ TOF measurement for heavy particles
  - ✓ Particle ID



Neutron detector array

- ✓ Acceptance = 100 ~ 300 mSr
- ✓ $\Delta E/E \sim 5.0 \times 10^{-2}$ via TOF measurements

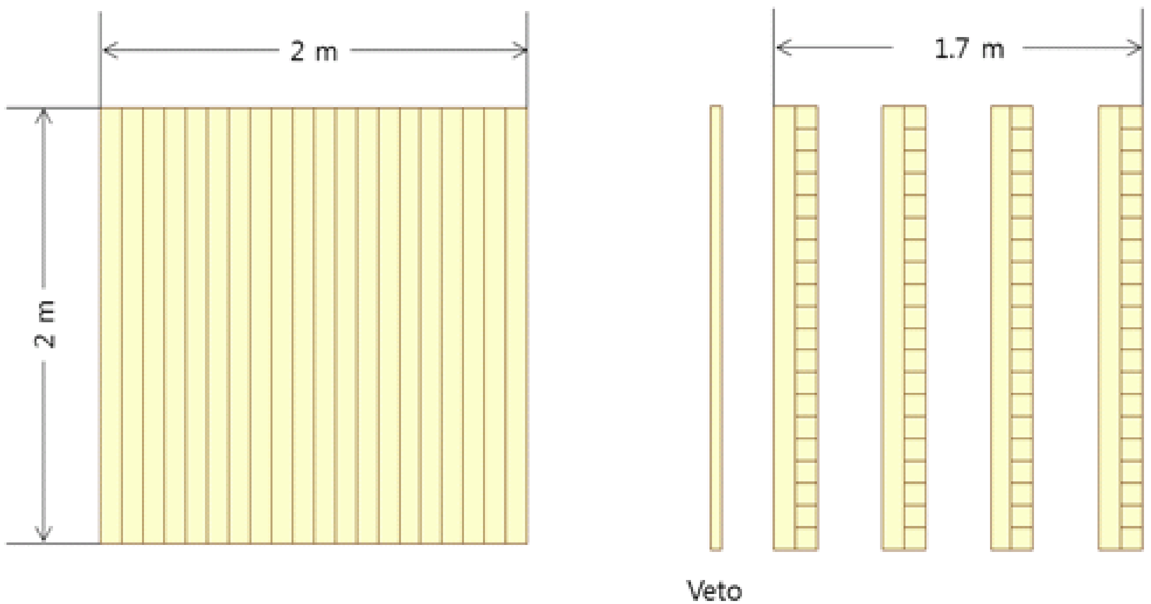




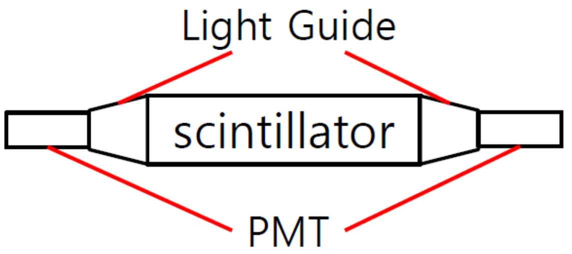
3. Neutron detectors for high-energy experiment

Proposed structure: 4 layers of plastic scintillators (2-m long)
+ 1 Veto plastic layer for charged particle rejection

- ✓ Energy range to measure: 10 ~ 300 MeV
- ✓ Acceptance = 100 mSr
- ✓ $\Delta E/E$ ~ 2 x 10^{-2} via TOF measurements
- ✓ ε = 0.60 for single-neutron events (GEANT4)
  = 0.18 for double-neutron events (GEANT4)

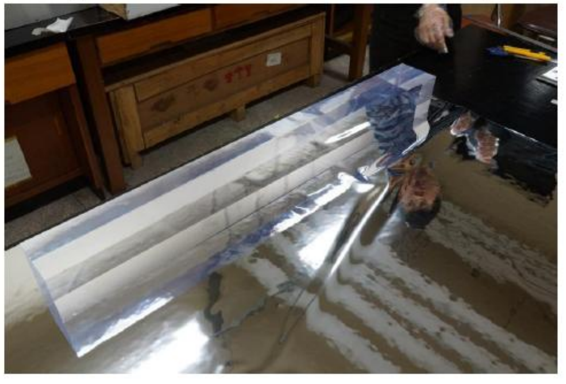


Single detector module for high-energy experiment



- n-p elastic scattering
- n-^{12}C elastic scattering
- n+p → d+γ (neutron capture, E_γ = 2.23 MeV)
- n+^{12}C → ^{13}C+γ (neutron capture, E_γ = 1.2, 3.6, 4.9 MeV)

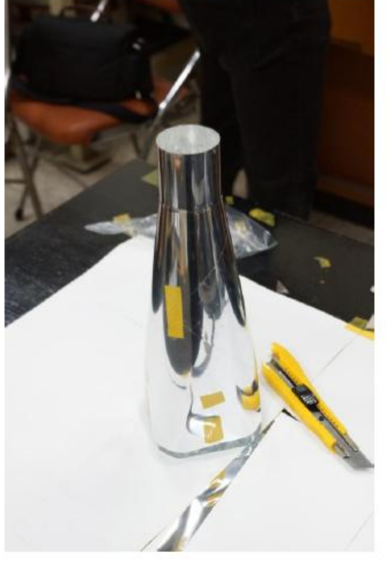
scintillator



Bicron BC-408

Decay constant: 2.1 ns
Bulk light attenuation length: 380 cm
Refractive index: 1.58
H:C ratio: 1.104
Density: 1.032
Softening point: 70 ℃₩

Light guide



Arcrylic

Density: 1.18 g/cm3
Refractive index: 1.4914

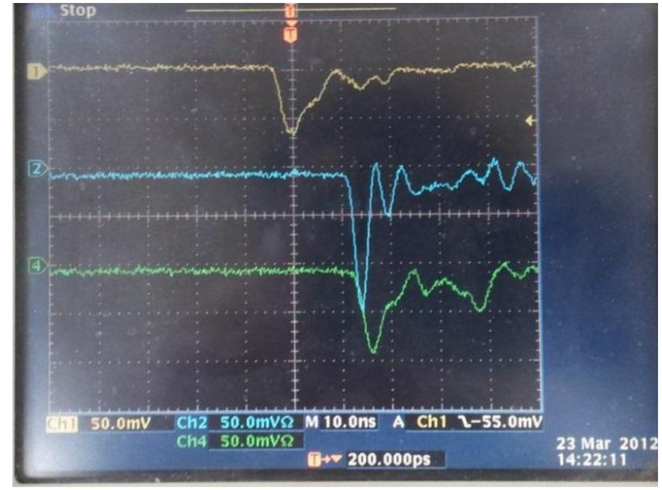
PMT

H2431-50

Wavelength short: 300 nm
Wavelength long: 650 nm
Transit time: 16 ns
Gain: 2.5e+6

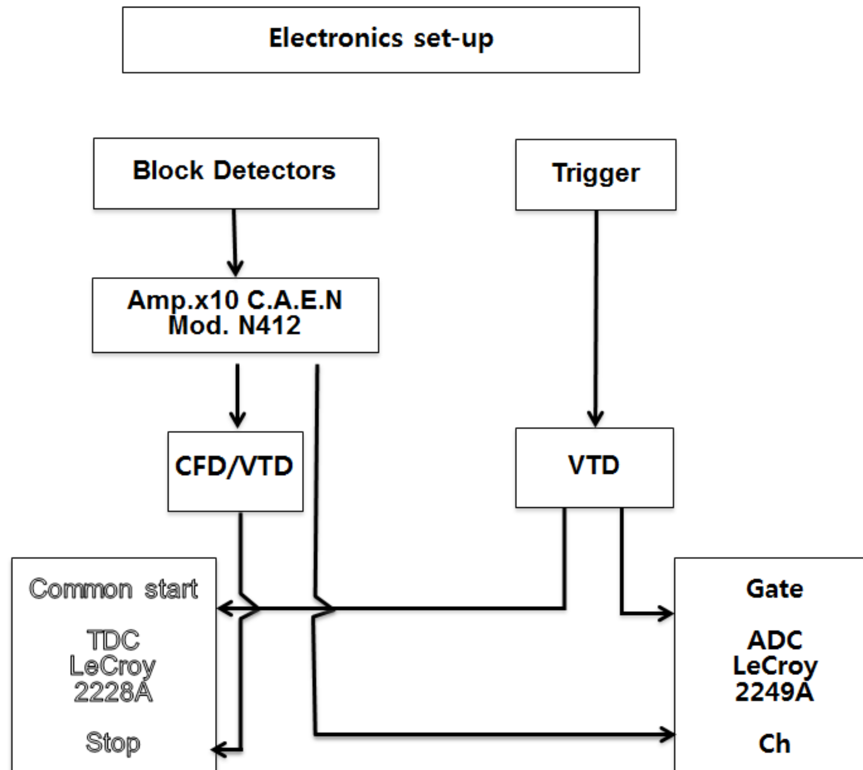
Test with a ^{60}Co & ^{252}Cf sources

- Time-Of-Flight for γ and n
- TOF distance = 1.0 m
- 5-cm thick 5-cm diameter disk-shape plastic scintillator for event triggers
- Maximum TOF to measure = 50 ns
- 3.78 n per fission decay and γ's from gamma transitions

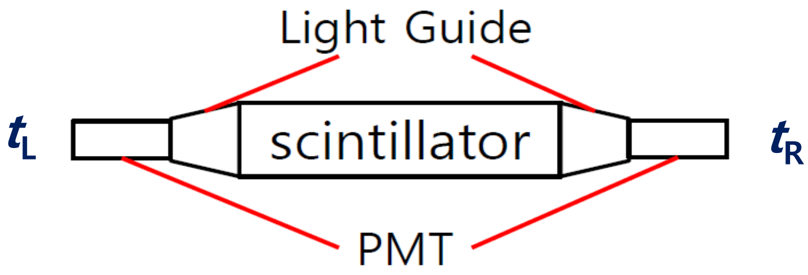


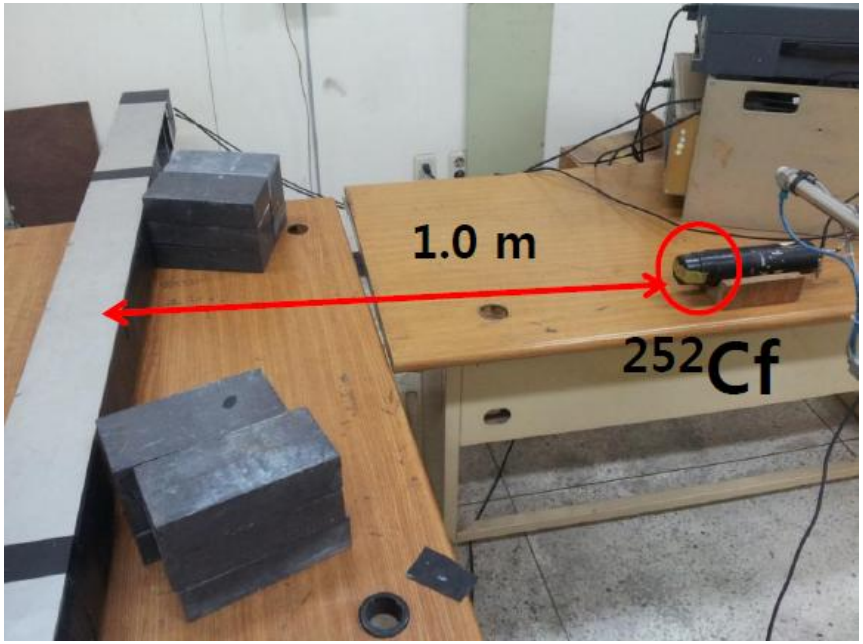
Event triggers

Trigger detector	Neutron detector
γ	γ
n	γ
γ	n
n	n

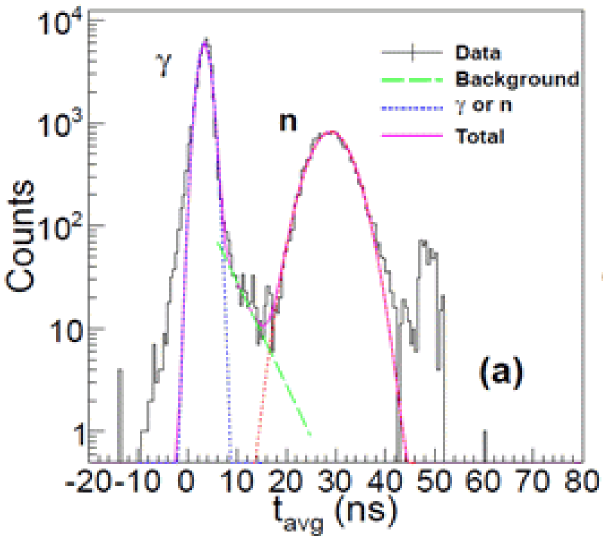


TOF measurement for fission neutrons and gammas from ^{252}Cf

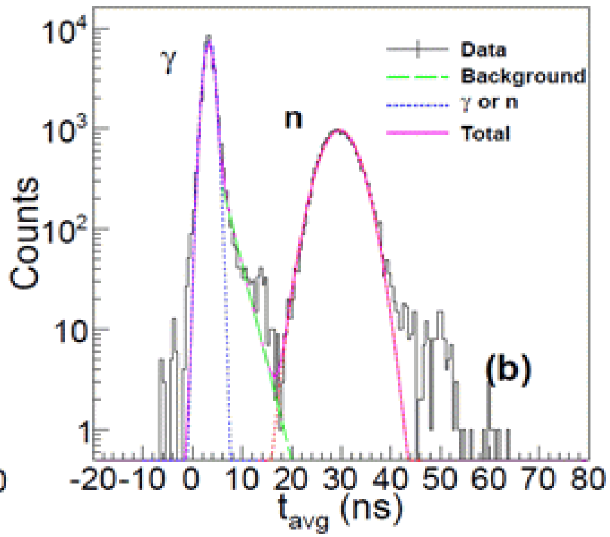


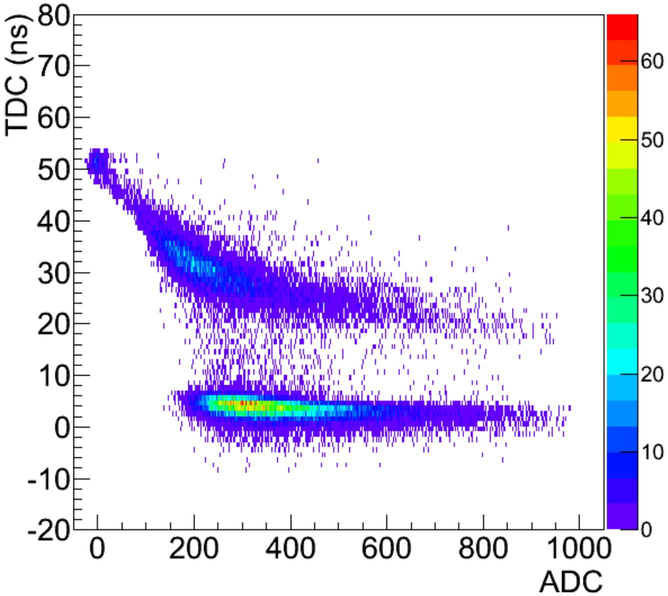


From Left PMT



From Right PMT

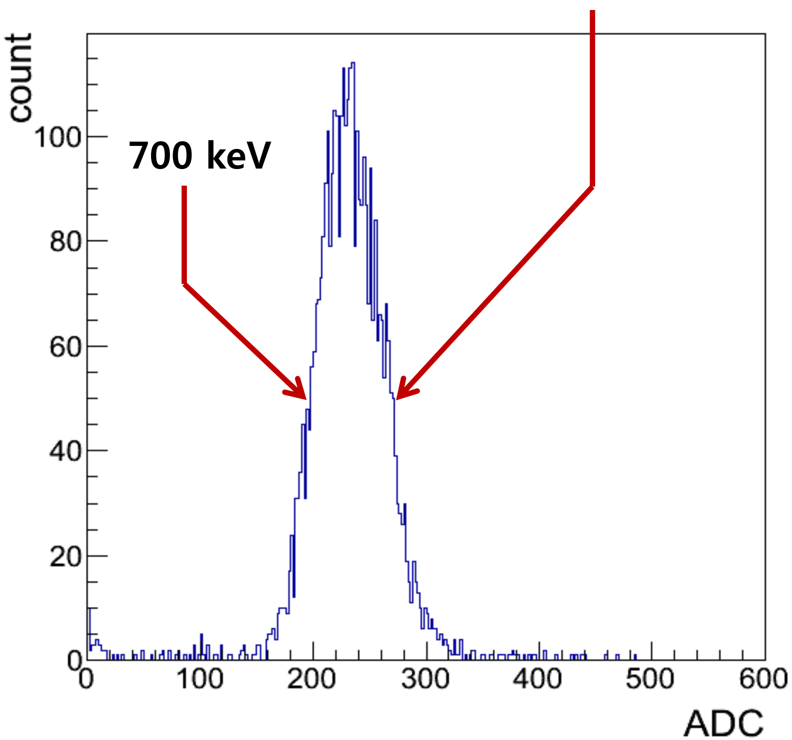


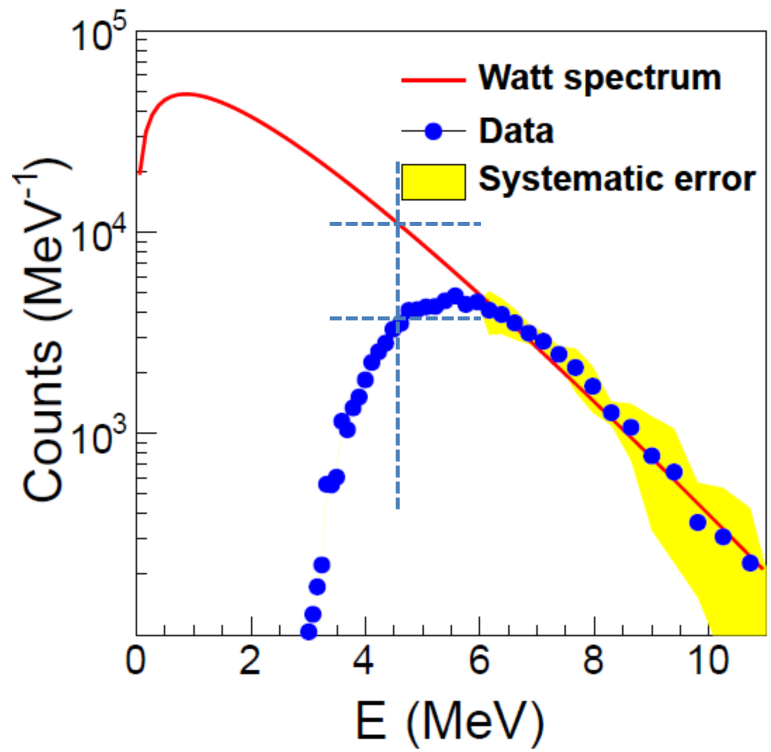


1-m bar unit detector for high-energy experiments

- ✓ Time resolution ~ 600 ps
- ✓ Position resolution ~ 8.0 cm
- ✓ Electron-equivalent energy with 50% efficiency ~ 700 keV
- ✓ Neutron energy with 50% efficiency ~ 4.5 MeV

Compton edge for 1.17 & 1.33 MeV γ's from ^{60}Co ~ 1.0 MeV

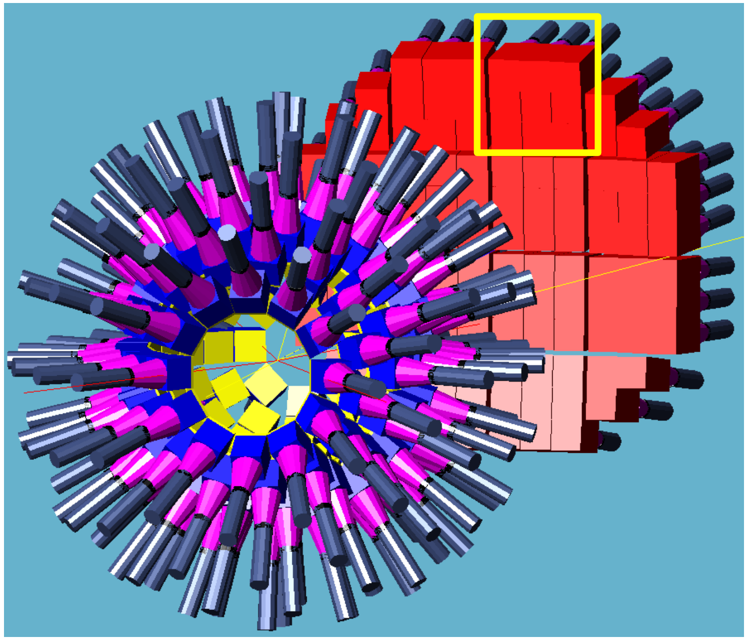


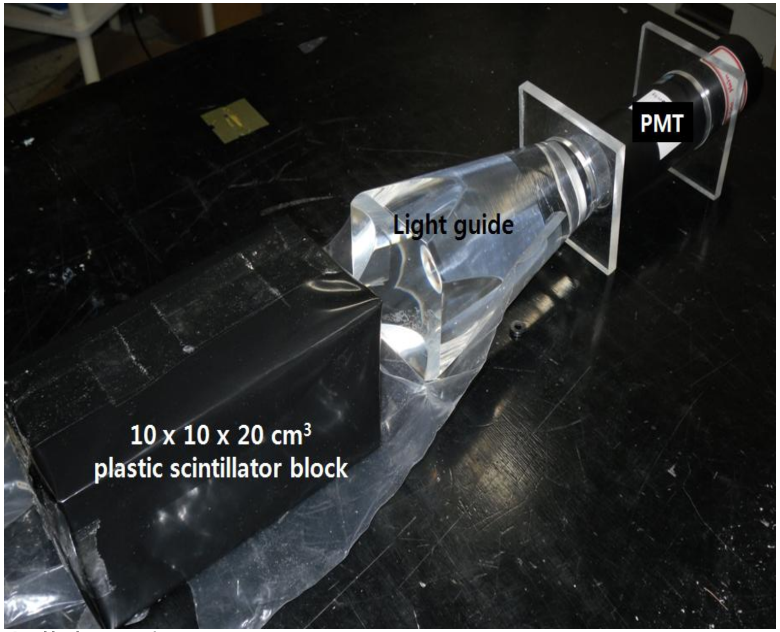


J. Kor. Phys. Soc. 58 (2011) 211
J. Kor. Phys. Soc. 62 (2013) 1227

4. Neutron detectors for low-energy experiment

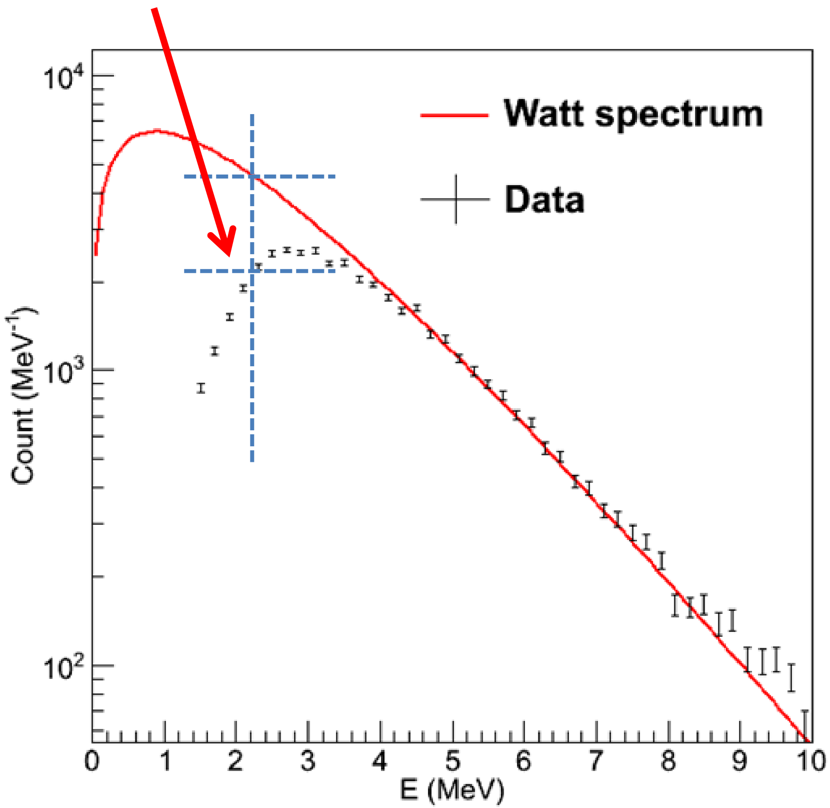
- Neutron energy range to detect with ε > 0.7 = 2.5 ~ 30 MeV
  - ✓ Minimum detectable energy ~ 1 MeV with 300-ns TOF
- Basic structure of unit pixel detector: 3 x 3 detector modules
  - ✓ Single detectors: 10 x 10 x 20-cm^3 plastic scintillator blocks
- Neutron energies measured by a TOF method
  - ✓ $\Delta E/E \sim 5.0 \times 10^{-2}$ assuming a 3-m-long TOF length
  - ✓ Depth-of-interaction in the 20-cm long detector → Energy resolution





Pixel detectors for low-energy experiments

- ✓ Maximum TOF set to 80 ns
  → 1.4 MeV neutrons (efficiency ~ 0.2)
- ✓ Electron-equivalent energy with 50% efficiency ~ **300 keV**
- ✓ Neutron energy with 50% efficiency ~ **2.2 MeV**



Advantage of using pixel detectors

- ✓ Light-collection efficiency is higher (Light guide: 21 cm → 5 cm)
- ✓ Expect reconstruction of neutron hits becomes easier
  → Conductive to multi-neutron events

5. Summary & milestones

1. R&Ds of neutron detectors for LAMPS

- The proposed designs and the performances of the unit-detector relevant and satisfactory for Symmetry-Energy research

2. Bar-shape neutron detectors for high-energy experiments

- Detectable range of neutron energy confirmed > 5.0 MeV
- Time resolution ~ 600 ps → $\Delta E/E \sim 2 \times 10^{-2}$ via TOF at 15 m from a target
- Position resolution confirmed ~ 8 cm

3. Pixel-type neutron detectors for low-energy experiments

- Minimum neutron energy confirmed with ε > 50% < 2.5 MeV
- Depth-of-interaction of 20-cm long detectors: $\sigma \sim 7.0$ cm

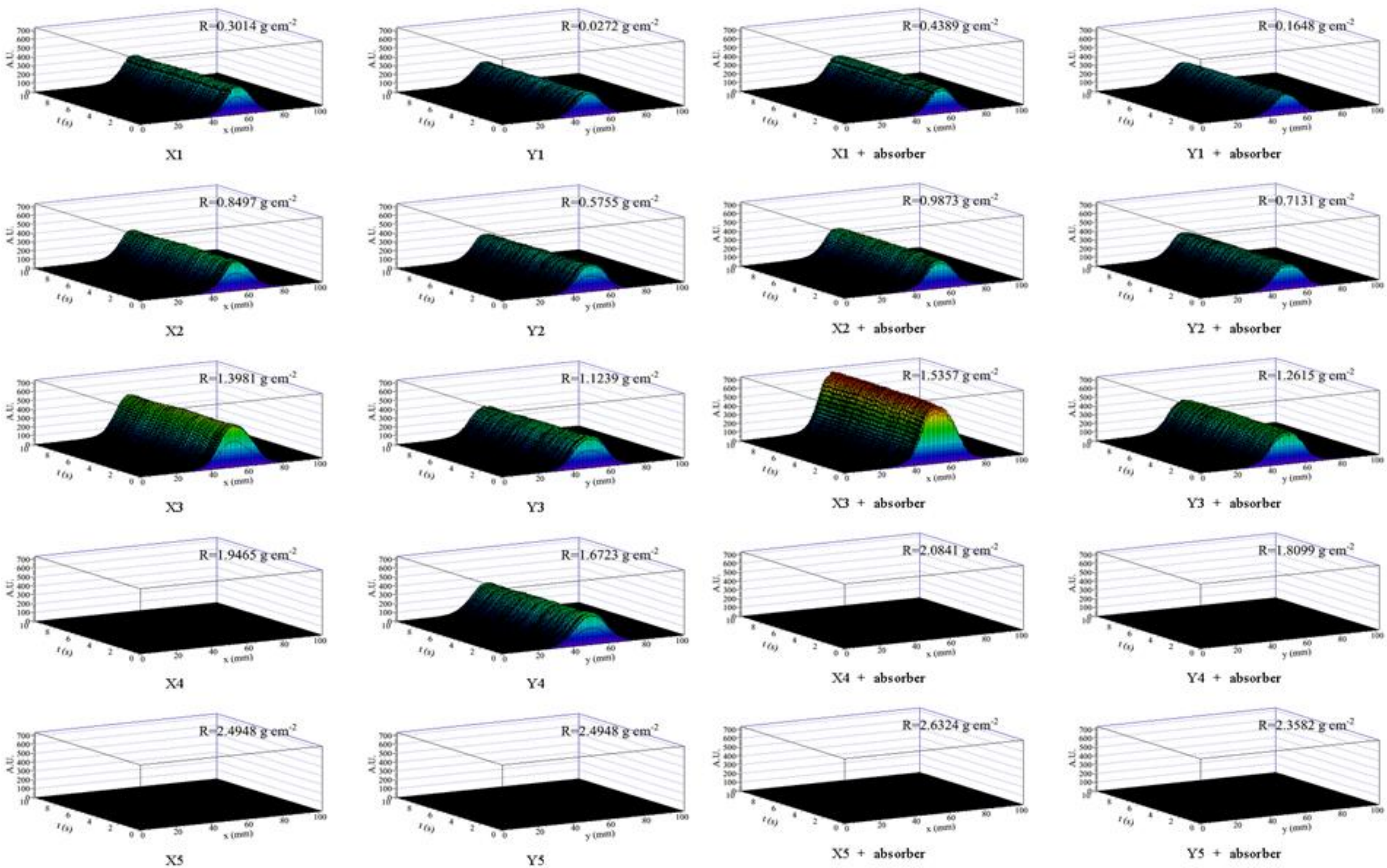
  → $\Delta E/E \sim 5 \times 10^{-2}$ via TOF measurements

4. Designs of electronics and DAQ for LAMPS neutron detectors

- Combined modules for discriminations, multi-hit TDC, and FADC
- 3.5 Gbps data bus electrons to counting rooms

Backup

Detector response for 10 s (bin size = 4-ms) **Fluctuation in time = 3% in sigma**



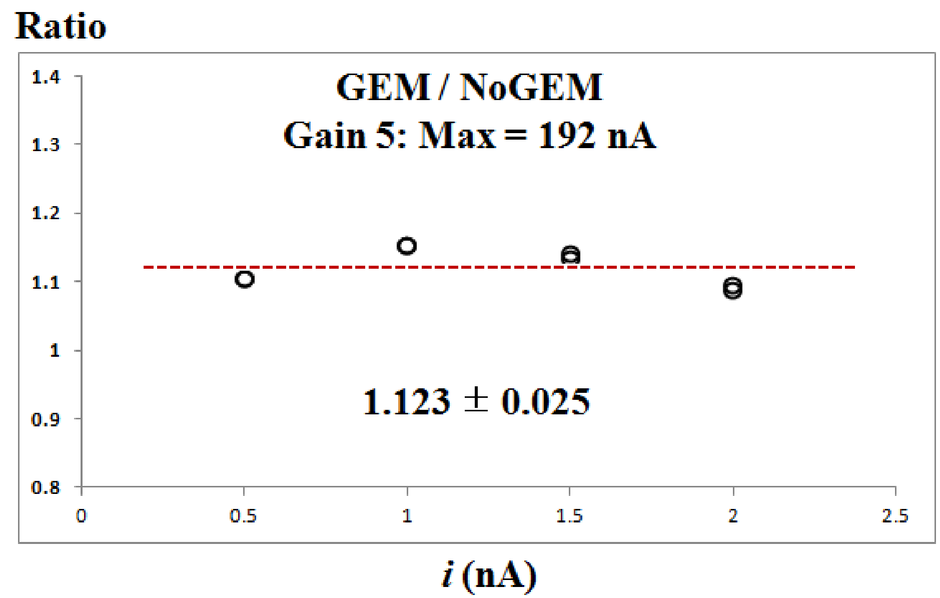
Ratios of the induced charge

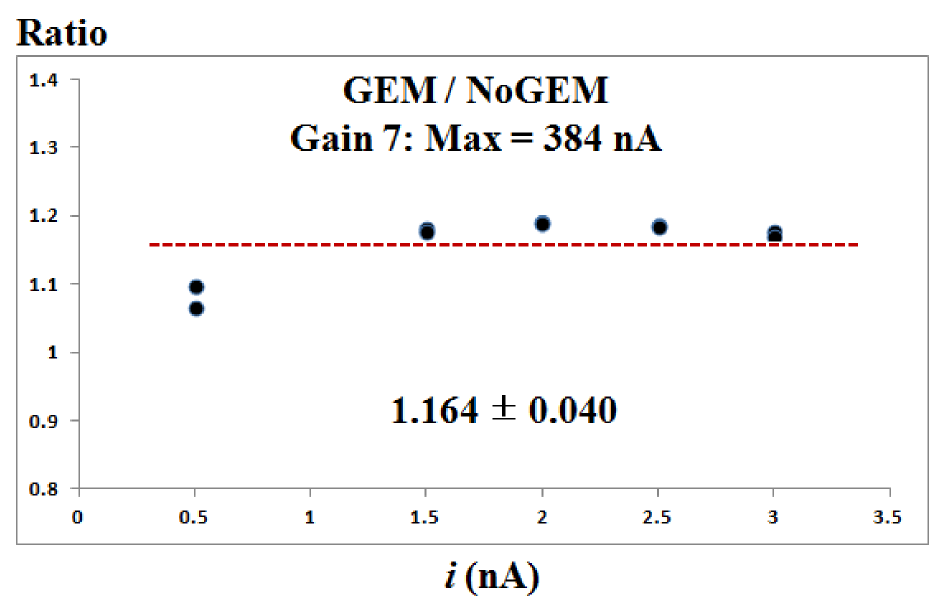
$$q_{GEM}/q_{NoGEM} = 1.144 \pm 0.033$$

Maximum 192 nA/ch at Gain 5

Maximum 384 nA/ch at Gain 7

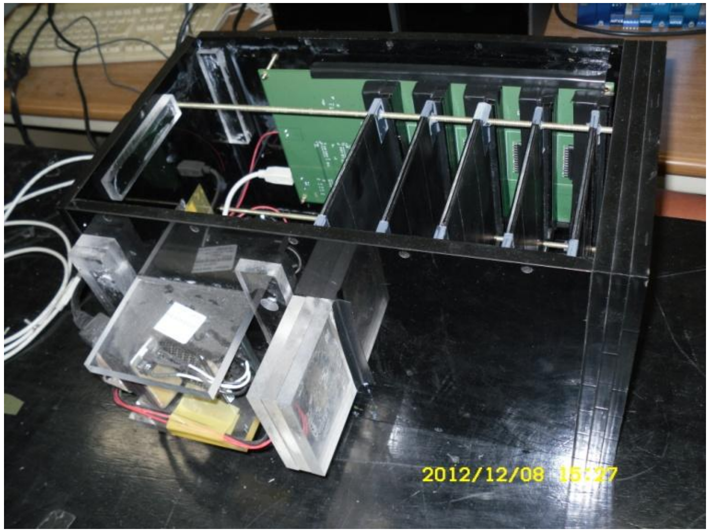
Accuracy of measuring beam induced charges for a single detector = 2.0%

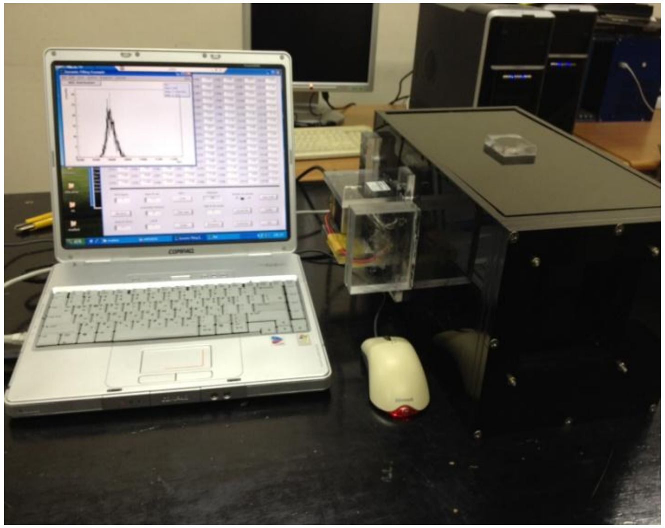


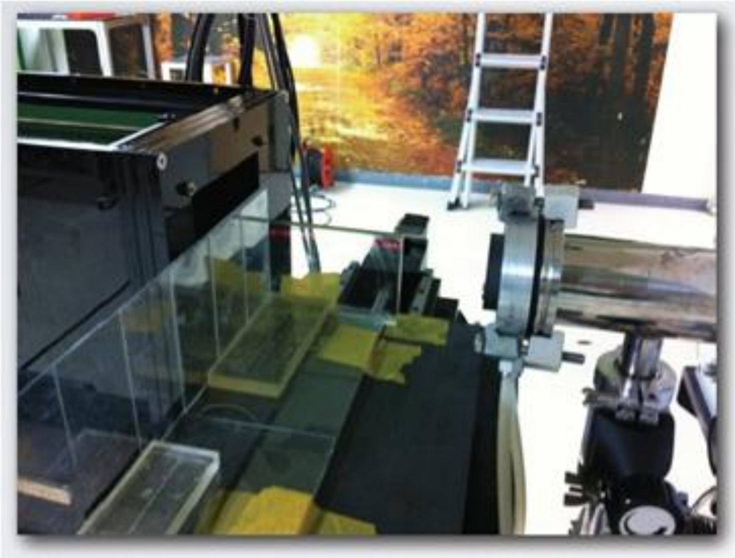


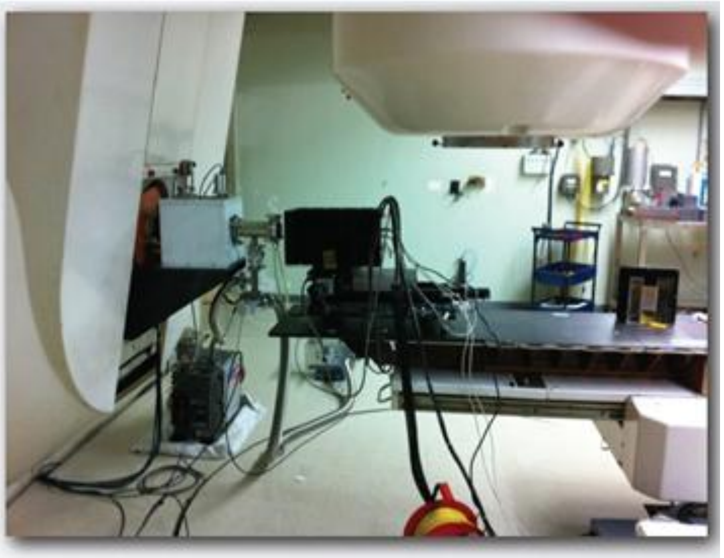
Tests with MC50 proton beams at KIRAMS

- 1.0-nA pencil and dispersed beam for calibration
- 0.5-nA pencil beam for dose measurements









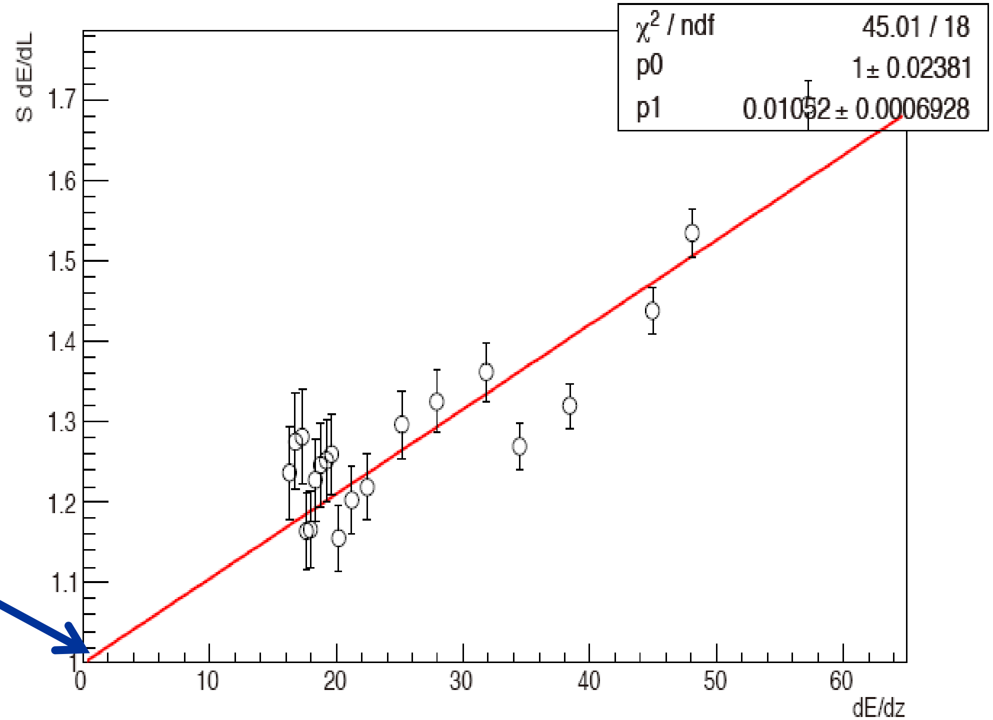
Nonlinearity of scintillation response to ELOSS

→ Birk's model with two parameters, 1st order *kB* and 2nd order *C*

$$\frac{dL}{dz} = \frac{S dE/dz}{1 + kB dE/dz + C(dE/dz)^2},$$

No quenching limit for a MIP proton

Expected to be *S dE/dL = 1* at ~ 2 MeV g cm^{-2}



Measurement for BCF-60 scintillation fibers

kB = (0.981±0.033) x 10^{-2} g cm^{-2} MeV^{-1}

→ **Close to typical plastic scintillators**

Scintillation-fiber-based detector for therapeutic beams (~ 180 MeV protons)

Merits

- **Scintillation fiber → solid detector**

  → Data are quantitatively reliable and insensitive to environmental conditions (*T* & *P*), compared to gaseous detectors

- **Thin detector thickness to form multi-layer detector structure**

  → Enable to perform simultaneous measurement along the beam range

- **Scintillation fiber with ρ = 1.05 g cm^{-3}**

  → Enable to manufacture the detector system **water equivalently.**

  → The detector itself is an **water-equivalent phantom** (also ~ tissue equivalent).

- **Relatively low-price multi-channel photodiode for the signal process**

  → **Multi-layer detector system equipped with more than 1000 channels**

Drawback

- **Scintillation fiber is an organic scintillator**

  → **Quenching of signals**

  → Difficulty in correction for nonlinearity response to ELOSS

Importance of Symmetry Energy

Effective field theory, QCD

π^-/π^+
K^+/K^0
n/p
$^3H/^3He$
γ

Isospin Dependence of Strong Interactions

Nuclear Masses
Neutron Skin Thickness
Isovector Giant Dipole Resonances
Fission

Heavy Ion Flows
Multi-Fragmentation
Nuclei Far from Stability
Rare Isotope Beams

isodiffusion
isotransport
+ isocorrelation
isofractionation
isoscaling

Many-Body Theory
Symmetry Energy
(Magnitude and Density Dependence)

Supernovae
Weak Interactions
Early Rise of $L_{\nu e}$
Bounce Dynamics
Binding Energy

Proto-Neutron Stars
ν Opacities
ν Emissivities
SN r-Process
Metastability

Neutron Stars
Observational
Properties

Binary Mergers
Decompression/Ejection
of Neutron-Star Matter
r-Process

QPO's
Mass
Radius

NS Cooling
Temperature
R_∞, z
Direct Urca
Superfluid Gaps

X-ray Bursters
R_∞, z

Gravity Waves
Mass/Radius
dR/dM

Pulsars
Masses
Spin Rates
Moments of Inertia
Magnetic Fields
Glitches - Crust

Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates

- A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Report 411, 325 (2005)

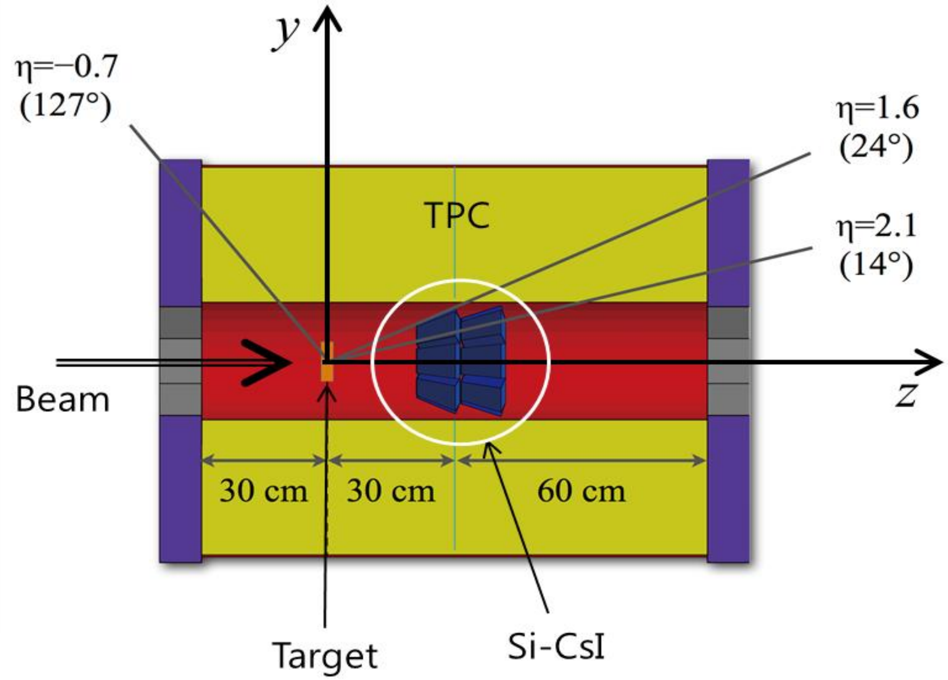
Experimental Observables

- **Signals at sub-saturation densities**
  1) **Sizes of n-skins for unstable nuclei**
  2) **n/p ratio of fast, pre-equilibrium nucleons**
  3) **Isospin fractionation and isoscaling in nuclear multifragmentation**
  4) **Isospin diffusion (transport)**
  5) **Differential collective flows (v_1 & v_2) of n and p**
  6) **Correlation function of n and p**
  7) **$^3H/^3He$ ratio, etc.**
- **Signals at supra-saturation densities**
  1) **π^-/π^+ ratio**
  2) **Differential collective flows (v_1 & v_2) of n and p**
  3) **Azimuthal angle dependence of n/p ratio with respect to the R.P.**
- **Correlation of various observables**
- **Simultaneous measurement of neutrons and charged particles**

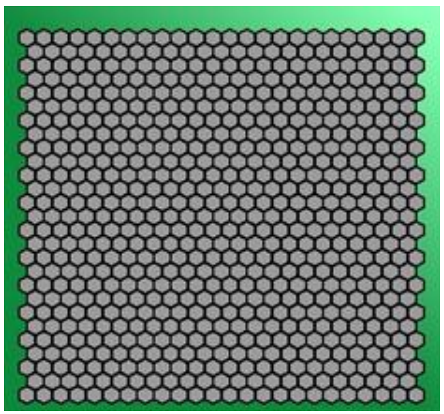
TPC

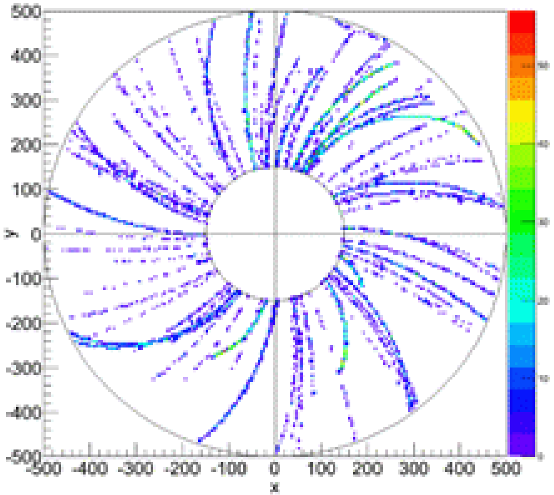
- ✓ Gas: P10 or Ar +CO_2 mixture
- ✓ Drift field: ~ 150 V cm^{-2}
- ✓ Read-out: Triple-GEM & hexagonal pads (5 mm) at both endcaps

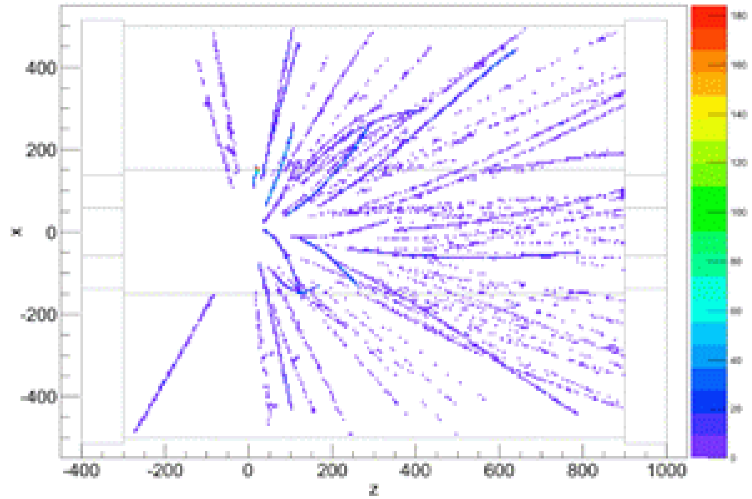
Choice of GEMs: higher rate capability of both heavily ionizing particles



Hexagonal pads for a prototype

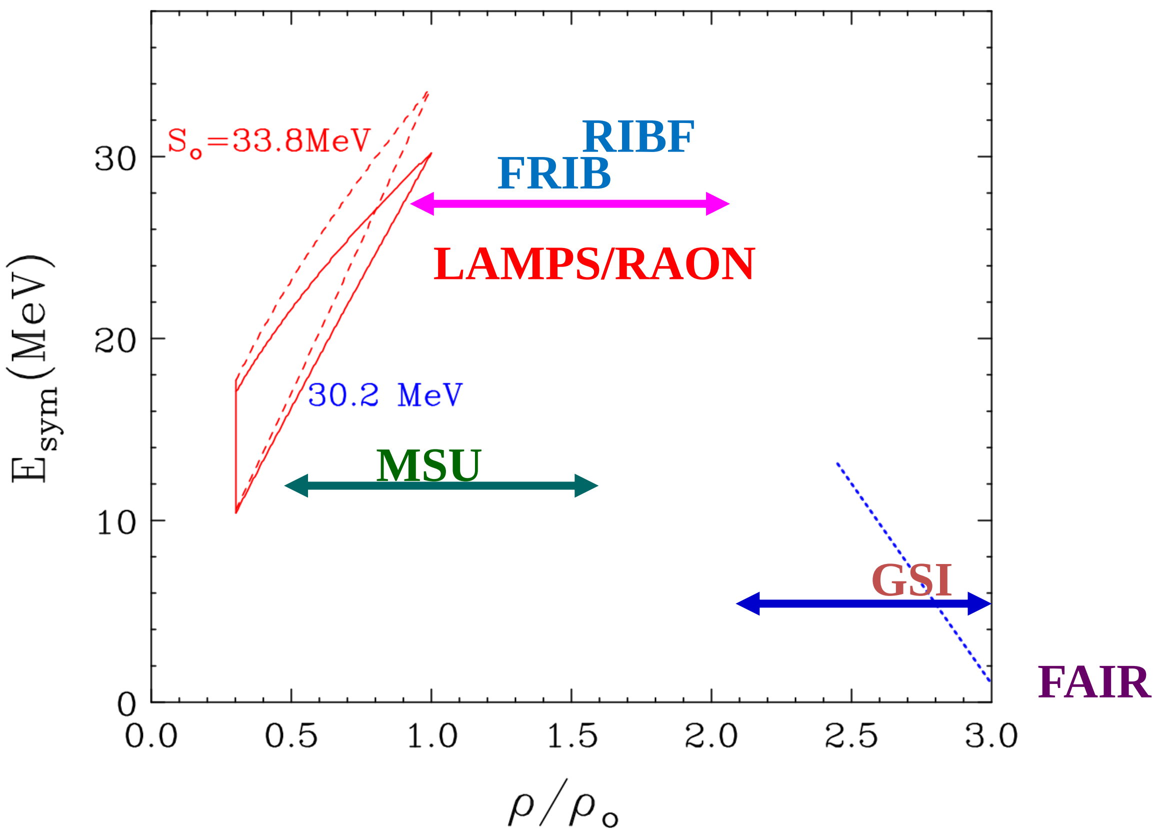






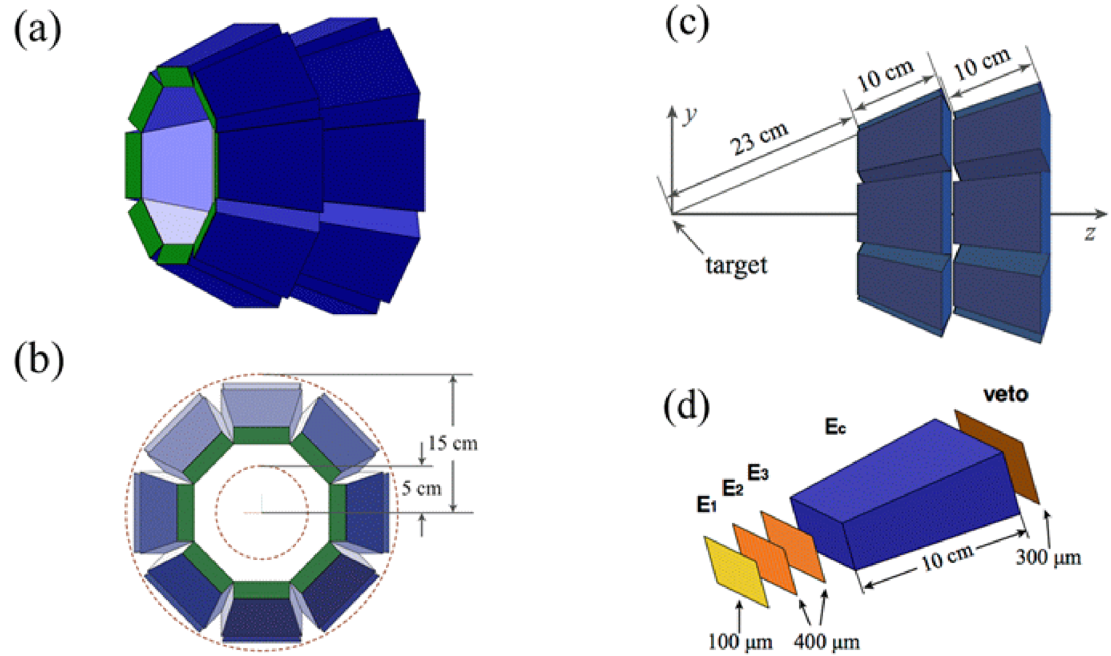
LAMPS/RAON: exploring a wide range of *N*/*Z* asymmetry

- **The symmetry energy at sub-saturation density and supra-saturation density with ~ 200 AMeV**

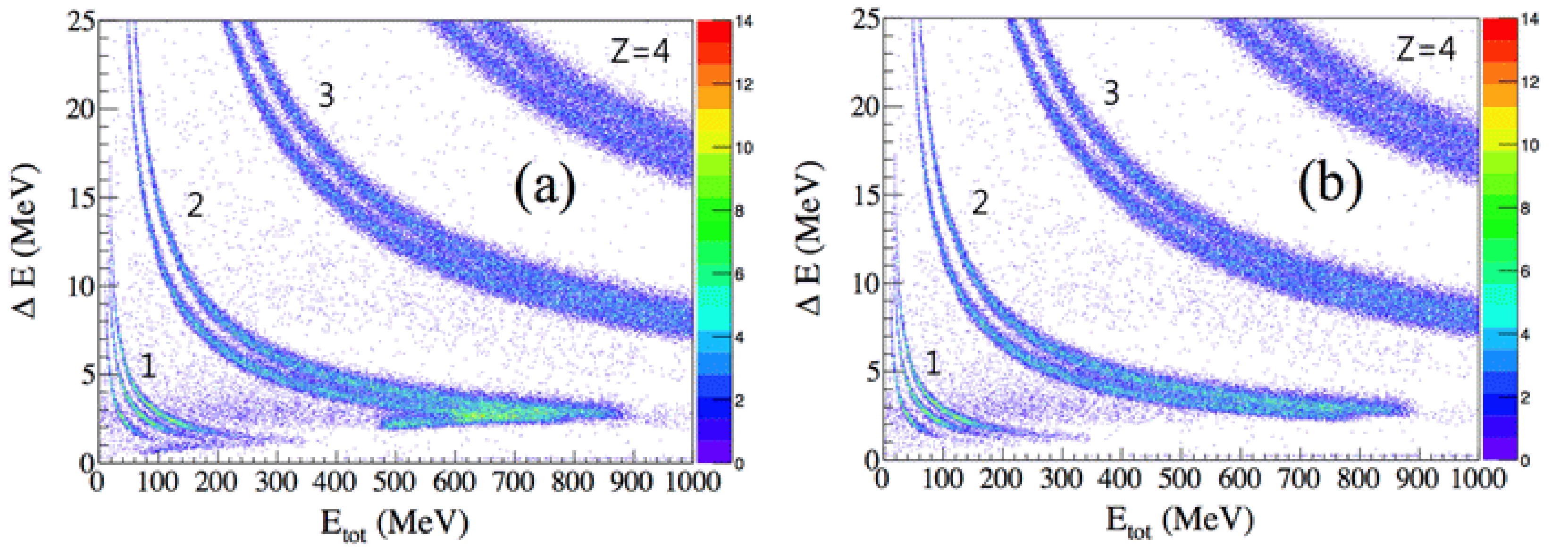


Si-CsI arrays

- ✓ Energy measurement and particle ID for high-η nuclear fragments
- ✓ Determination of reaction planes of HI collisions



GEANT4



Nuclear Equation of State

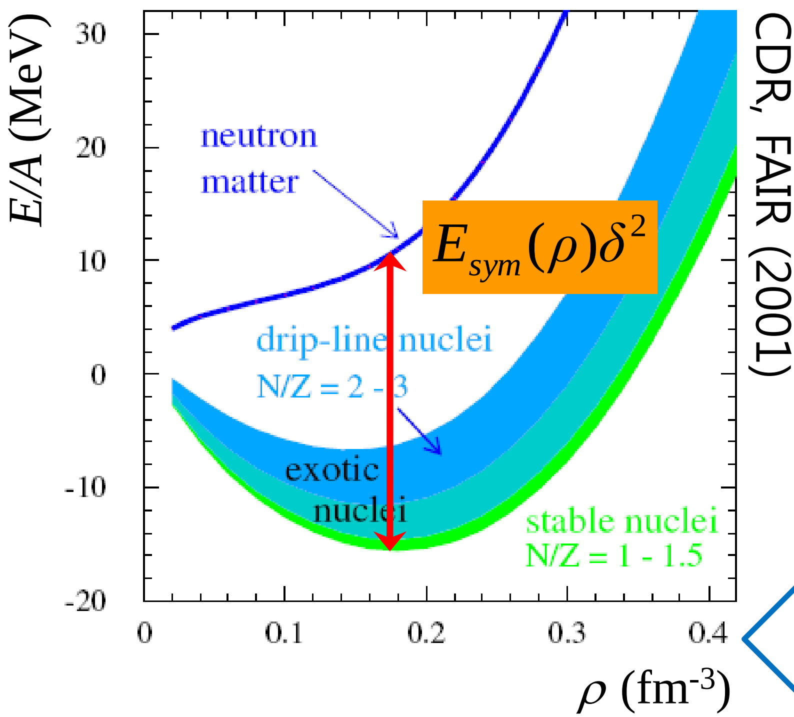
δ: asymmetry in p & n

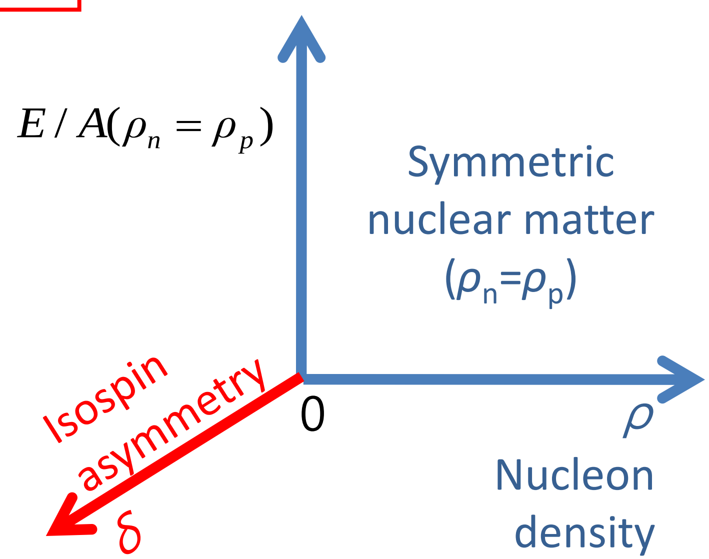
$$E(\rho_n,\rho_p) = E(\rho_n=\rho_p) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2} \approx E(\rho)_{\substack{\text{pure}\\ \text{neutron matter}}} - E(\rho)_{\substack{\text{symmetric}\\ \text{nuclear matter}}}$$

with $\rho = \rho_n + \rho_p,\ \delta = (\rho_n - \rho_p)/\rho = (N-Z)/A$

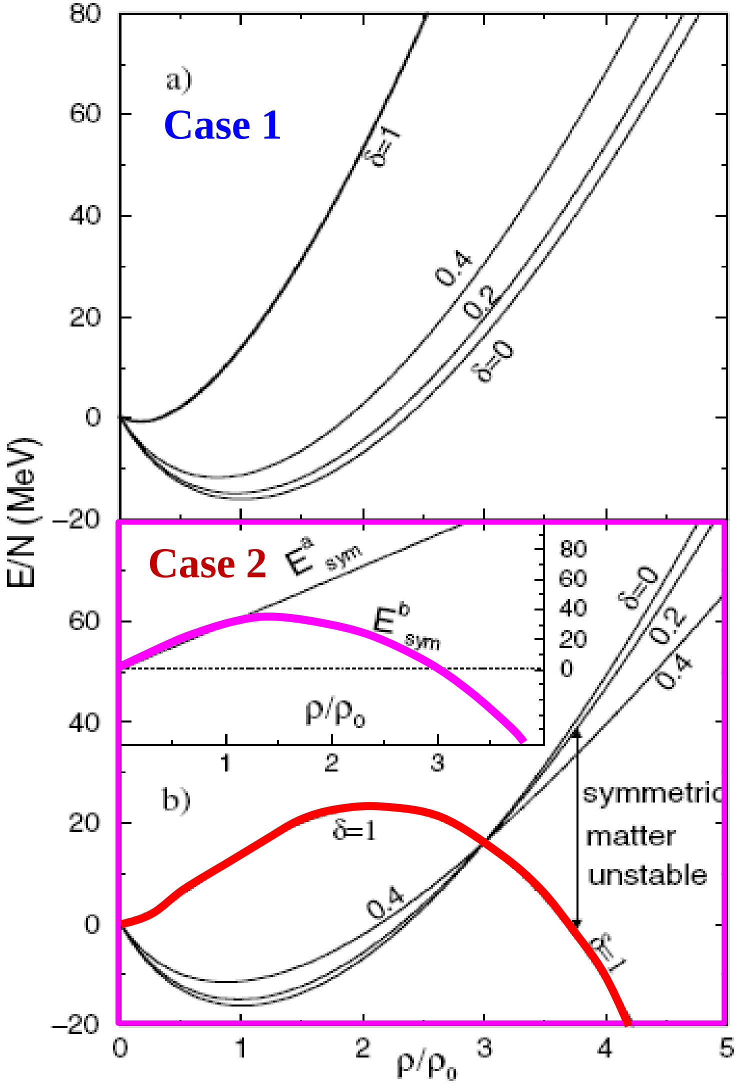
B.-A. Li, L.-W. Chen & C.M. Ko, Physics Report, 464, 113 (2008)





F. de Jong & H. Lenske, RPC 57, 3099 (1998)
F. Hofman, C.M. Keil & H. Lenske, PRC 64, 034314 (2001)

LAMPS probes symmetry-energy up to ρ_0/ρ ~ 2 with 200 AMeV

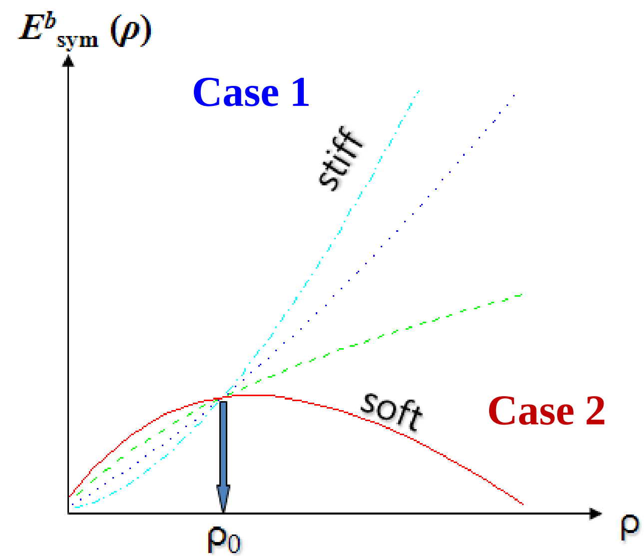


Bao-An Li, PRL 88, 192701 (2002)
Phys Rep. 464 113 (2008)

At nuclear matter density $\rho > \rho_0$ (= 0.16 fm^{-3})

Case 1: $E^a_{sym}(\rho) = E_{sym}(\rho_0)\, u,\ \ u_c = \rho/\rho_0$

Case 2: $E^b_{sym}(\rho) = E_{sym}(\rho_0)\, u\,(u_c - u)/(u_c - 1),\ \ u_c = \rho/\rho_0$



High (Low) density matter is more neutron rich with **soft (stiff)** symmetry energy

LAMPS: design for high-energy experiment

Solenoid spectrometer

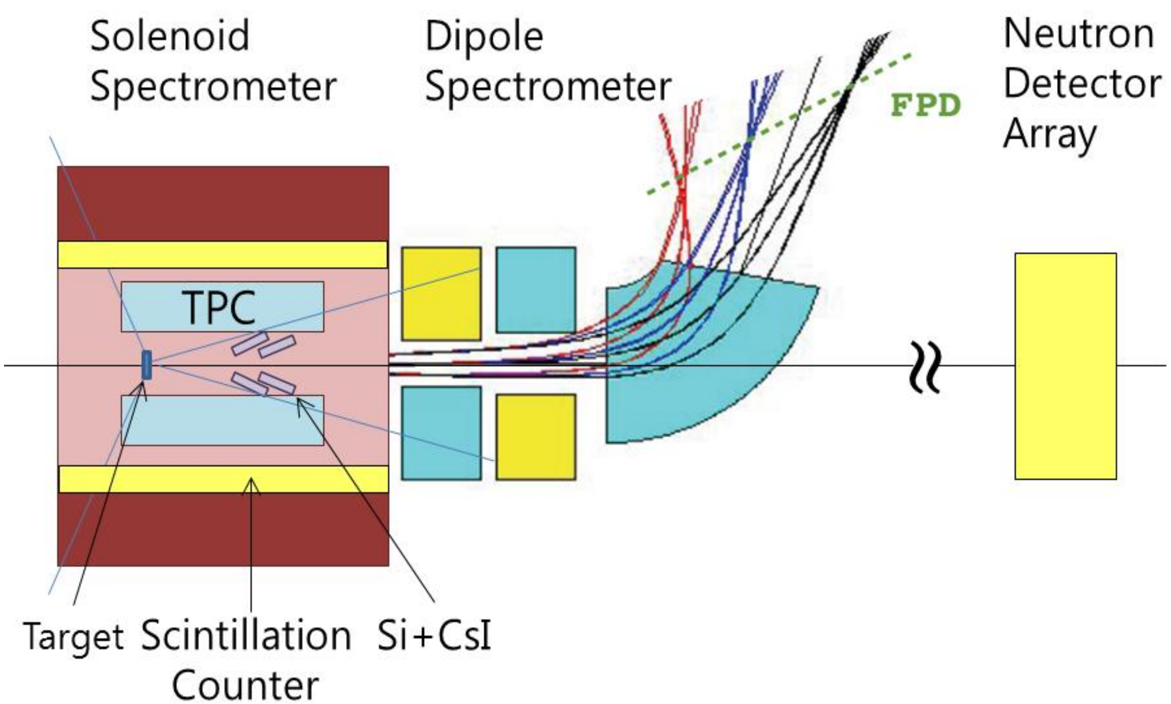
- Solenoid magnet (0.6 ~ 1.5 T)
- TPC ($\Delta P/P \sim 10^{-2}$)
- Si-CsI array ($\Delta E/E \sim 10^{-2}$)
- Plastic barrel detectors for trigger

Dipole spectrometer

- Quadruple-Dipole magnets (QD or QQD) for focal plane ($\Delta P/P \sim 4 \times 10^{-4}$)
- Drift chambers
- TOF wall

Neutron detector array

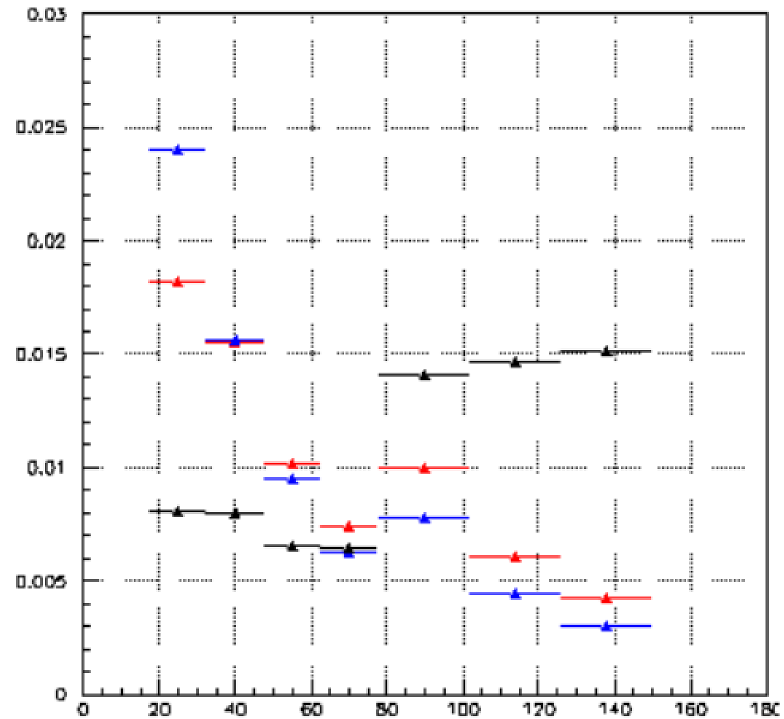
- Acceptance ~ 100 mSr
- $\Delta E/E \sim 2 \times 10^{-2}$

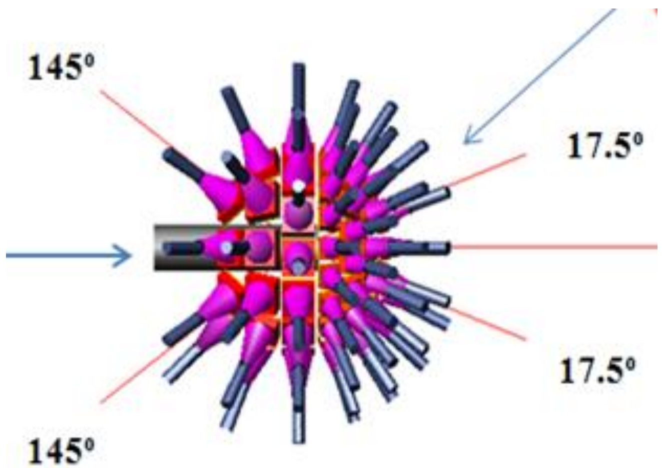


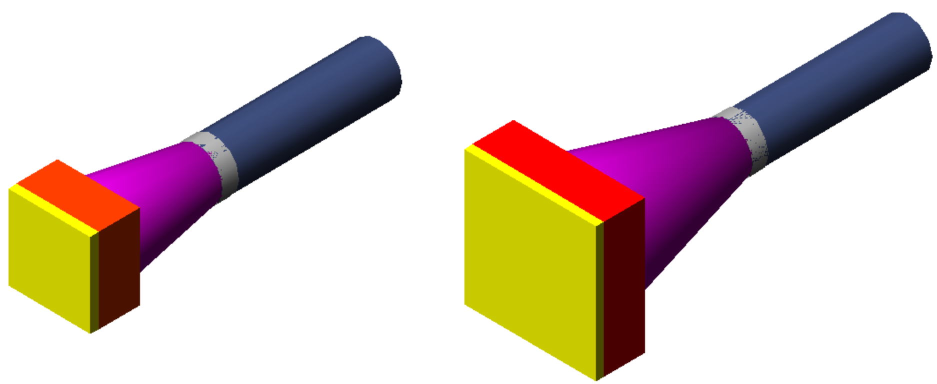
Si-CsI arrays

- Energy measurement and particle ID for both nuclear fragments and γ's
- 100 μm thick Si
- 50-mm thick CsI
  - ✓ Full absorption for all charged particles
  - ✓ ε > 70% for γ's
- Another solution
- Thin plastic-CsI arrays for measurement of lower-energy HI fragments

Particle occupancies (PHITS)
Black: all charge particles
Red: γ BLUE: protons



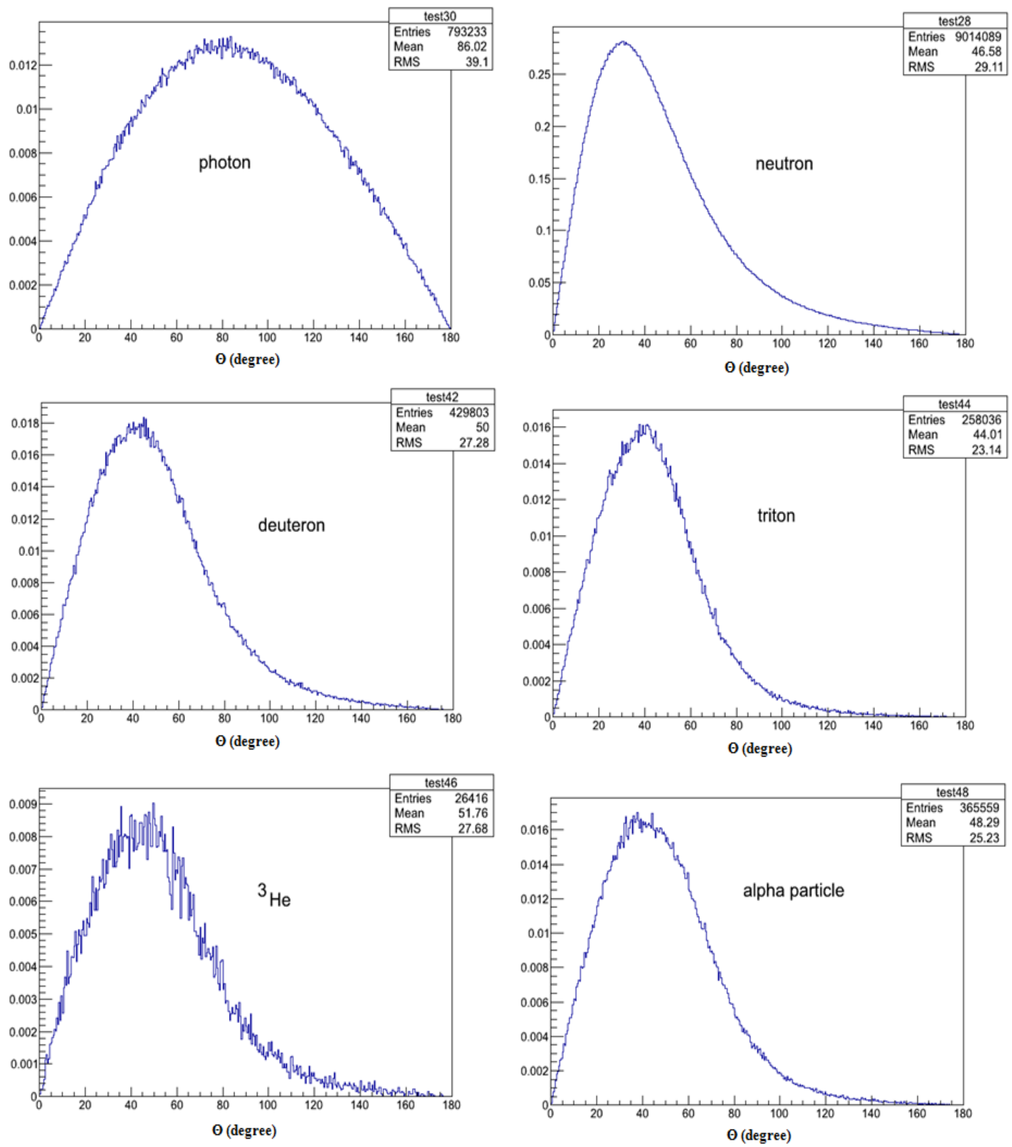




Beam schedule	Science program	Exp. facility♯	Beam species on exp. target†		Beam Intensity on exp. (pps) (required/expected)
			Day-1	Extra 2 years	
2018.Q2 ~ from SCL1 (<18.5 MeV/u)	Nuclear structure SHE search, rp-process, Spin physics	RS	^{54}Cr	^{64}Ni, ^{26m}Al (^{28}Si), ^{25}Al (^{28}Si), ^{44}Ti (^{42}Ca), ^{14,15}O (^{15}N)	^{15}N, ^{54}Cr, ^{28}Si, ^{42}Ca, ^{50}Ti, ^{25}Al, ^{26m}Al, ^{44}Ti, ^{14,15}O: (10^{5-6})
	Pigmy dipole resonance	LAS-L	^{58}Ni	^{40}Ca, ^{112}Sn	(10^{6-8} / <10^{9-10})
	Biological effects	BM	^{12}C		(<10^{12} / >10^{12})
	New materials, Polarized beam	β-NMR	^{8}Li by (d, n)(n,α) or (p,2p)		^{8}Li (10^{8} / 10^{9})
	Neutron cross section	NSF	n by (p,n) and (d,n)		n (< 10^{12} / 10^{12})
2019.Q4 ~ from ISOL (~5 keV/u)	Hyperfine structure, Mass measurement	Ion Trap LS	^{132}Sn	$^{130-135}$Sn	^{132}Sn (<10^{5} / 10^{7})‡, $^{130-135}$Sn (10^{3-6} / 10^{3-7})
2019.Q4 ~ ISOL-SCL3 (<18.5 MeV/u)	r-process	RS	^{132}Sn	$^{130-135}$Sn	^{132}Sn (10^{6} / 10^{7}), ^{65,66}Ni (10^{6-8} / 10^{6-7})
	Pigmy dipole resonance	LAS-L	^{132}Sn	$^{50+n}$Ca, $^{60+n}$Ni, $^{106+n}$Sn	
2019.Q4 ~ SCL1-SCL2 (~ hundreds MeV/u)	New materials	μSR	μ^{+} by (p, πx)		μ^{+} (10^{8} / 10^{9})
	Biological effects	BM	^{12}C		(<10^{12} / >10^{12})
	Baseline experiments, Spin physics	LAS-H	^{40}Ca	^{58}Ni, ^{112}Sn, ^{132}Xe	(10^{6-8} / <10^{9-11})
2020.Q2 ~ SCL1-SCL2-IF (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS	$^{100+n}$Sn	$^{100+n}$Sn	^{128}Sn (10^{6-8} / 10^{7}) ^{132}Sn (10^{6-8}/10^{7})‡
	Symmetry energy	LAS-H	^{132}Sn	$^{44+n}$Ca, $^{60+n}$Ni, $^{106+n}$Sn, ^{144}Xe	
2020.Q4 ~ ISOL-SCL3-SCL2-IF(X) (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS	^{132}Sn		^{132}Sn (10^{6-8} / 10^{7})‡ ^{144}Xe (10^{6-8} / 10^{6})
	Symmetry energy	LAS-H	$^{106+n}$Sn	$^{133+n}$Xe	
2021.Q2 ~ ISOL-SCL3-SCL2-IF (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS			^{78}Ni (/ <2)

♯ **RS**: Recoil Spectrometer, **LAS**: Large Acceptance Spectrometer, **BM**: Bio & Medical, **LS**: Laser Spectrometer, **NSF**: Neutron Science Facility, **ZDS**: Zero Degree Spectrometer, **HRS**: High Resolution Spectrometer † Beam species : **SI (black)**, **RI (Blue)** ‡ Beam purity >90 % for ISOL, 9% for IF

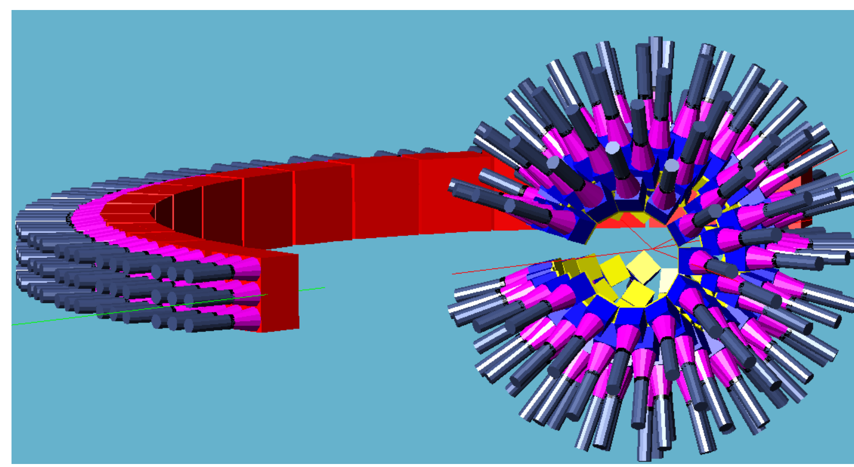
HI collision experiments for Symmetry-Energy with E_{beam} < 20 AMeV



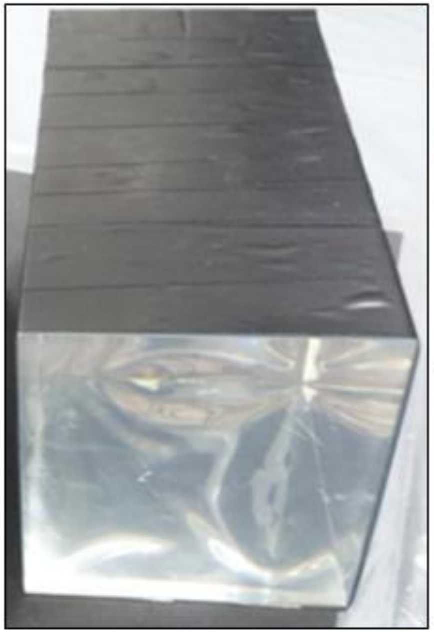
Simulation for 18.5-AMeV ^{132}Sn+^{124}Sn collisions in low-energy LAMPS experiment (Y. J. Kim, IBS)

Angular Distributions for
***γ, n, p, d,* ^{3}He, and ^{4}He**

PHITS (Particle and Heavy Ion Transport code System)



Single detectors using conical-shape light guides (3, 5, 21-cm long)



Unit detector module composed of 4-plastic scintillator blocks