Plan for the Study of Nuclear Symmetry Energy at RAON

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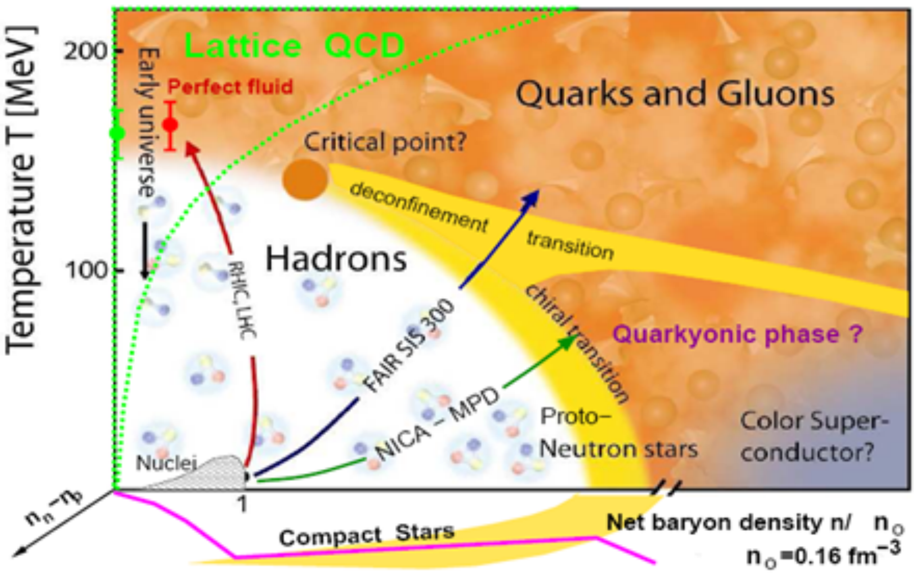
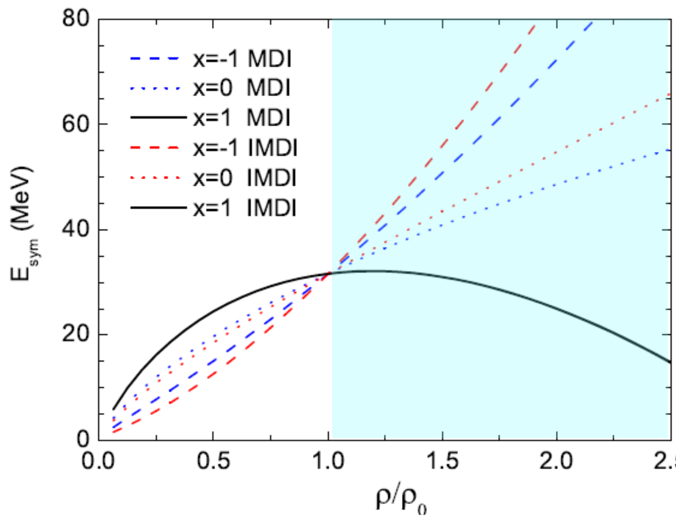
August 28th - 29th, 2015

Symmetry Energy Study at RAON

- **Exploring the nuclear phase diagram via heady-ion collisions including the isospin axis using RI beams**
- **Role of isospin degree of freedom in strong interaction**
  - **-Nuclear symmetry energy from sub- to supra-saturation densities**
  - **-Characterization of the core of neutron stars**

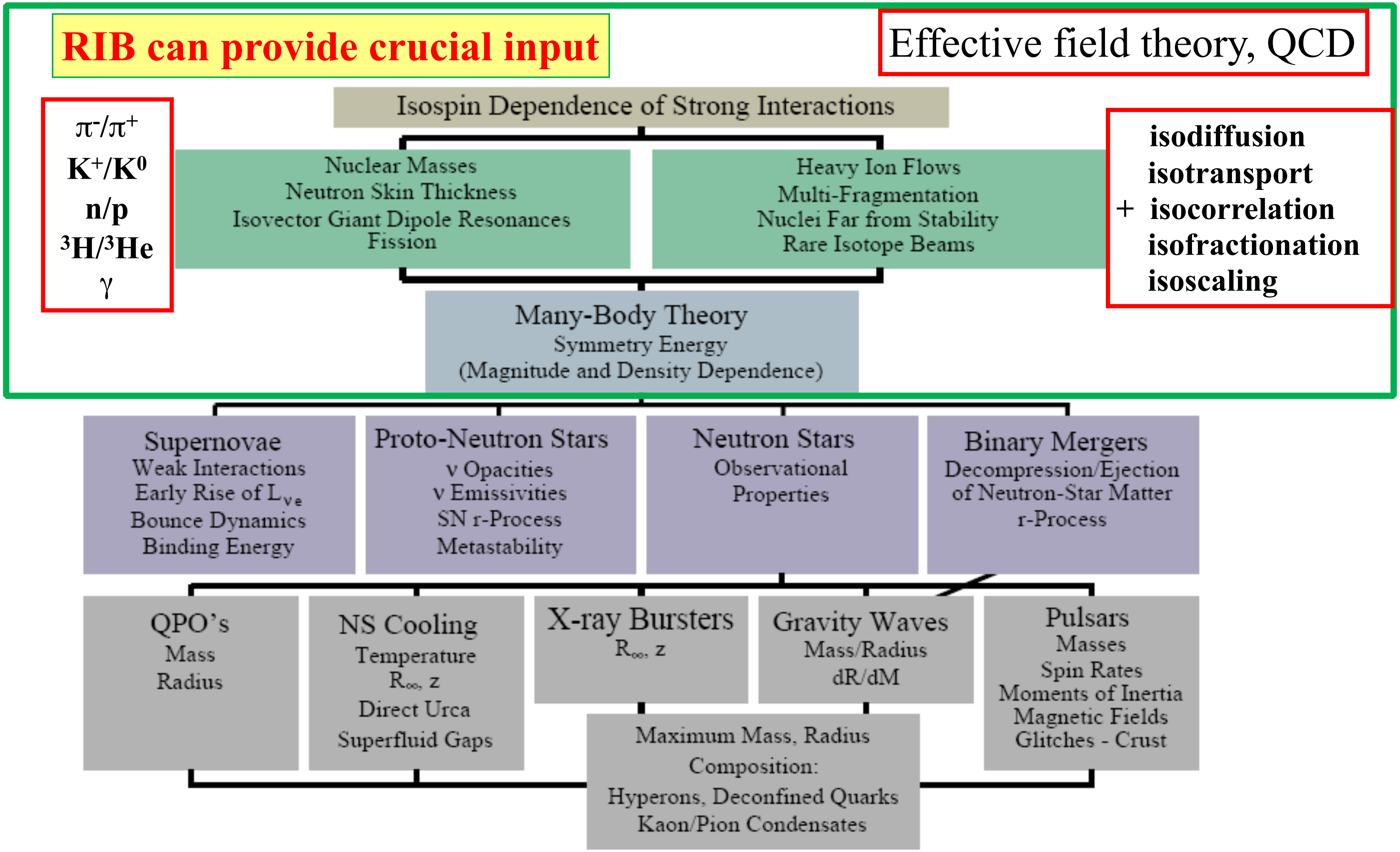




C. Xu and B. A. Li, PRC 81, 044603(2010)

LAMPS(Large Acceptance Multi-Purpose Spectrometer) is going to study of nuclear symmetry energy at supra-saturation density via heavy-ion collision experiment at RAON

Importance of Symmetry Energy



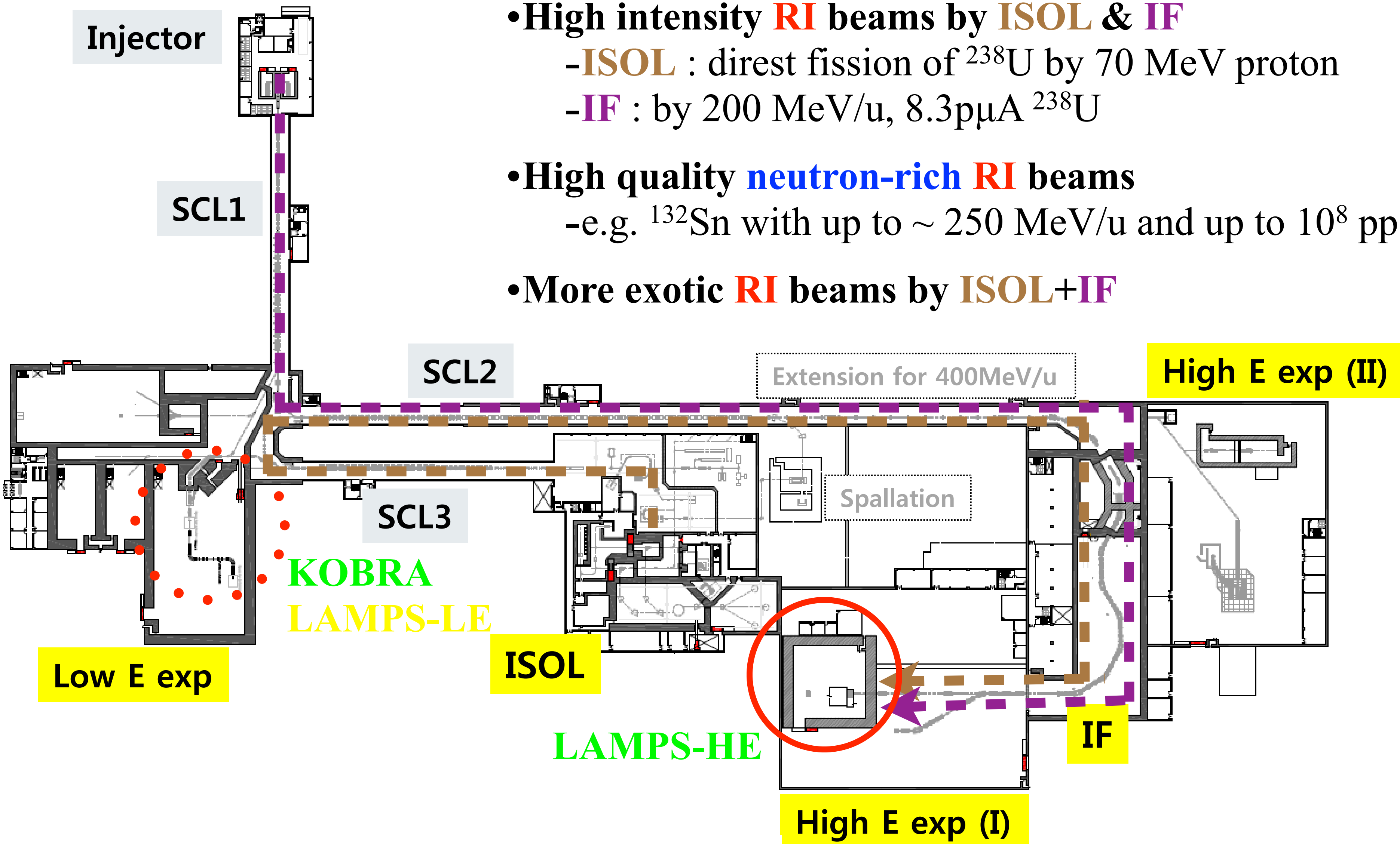
- **A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Report 411, 325 (2005)**
- **Red boxes: added by B.-A. Li**

Importance for understanding

- **Supernovae and neutron stars**
- **Nuclear synthesis and exotic nuclei near neutron drip lines**

RAON Accelerator Facility

- **High intensity RI beams by ISOL & IF**
  - -ISOL : direst fission of ^{238}U by 70 MeV proton
  - -IF : by 200 MeV/u, 8.3pμA ^{238}U
- **High quality neutron-rich RI beams**
  - -e.g. ^{132}Sn with up to ~ 250 MeV/u and up to 10^8 pps
- **More exotic RI beams by ISOL+IF**



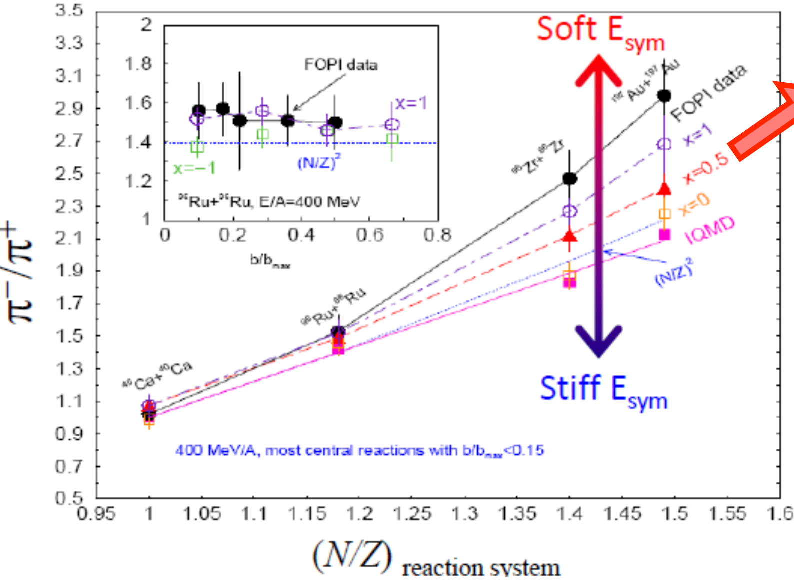
Physics Observables

Important to measure

system size (Ca, Ni, Ru, Zr, Sn, Xe, Au, U),
energy (lowest to top energies),
centrality, rapidity & transverse momentum dependence

1. Particle spectrum, yield, and ratio
    - n/p, ^{3}H(pnn)/^{3}He(ppn), ^{7}Li(3p4n)/^{7}Be(4p3n), $\pi^-(d\bar{u})/\pi^+(u\bar{d})$, etc
2. Collective flow
    - v_1 & v_2 of n, p, and heavier clusters
    - Azimuthal angle dependence of n/p ratio w.r.t the reaction plane
3. Various isospin dependent phenomena
    - Isospin fractionation and isoscaling in nuclear multifragmentation
    - Isospin diffusion (transport)
    - Etc.
4. Pygmy and Giant dipole resonances
    - Energy spectra of gammas
    - Related to the radius of n-skin for unstable nuclei

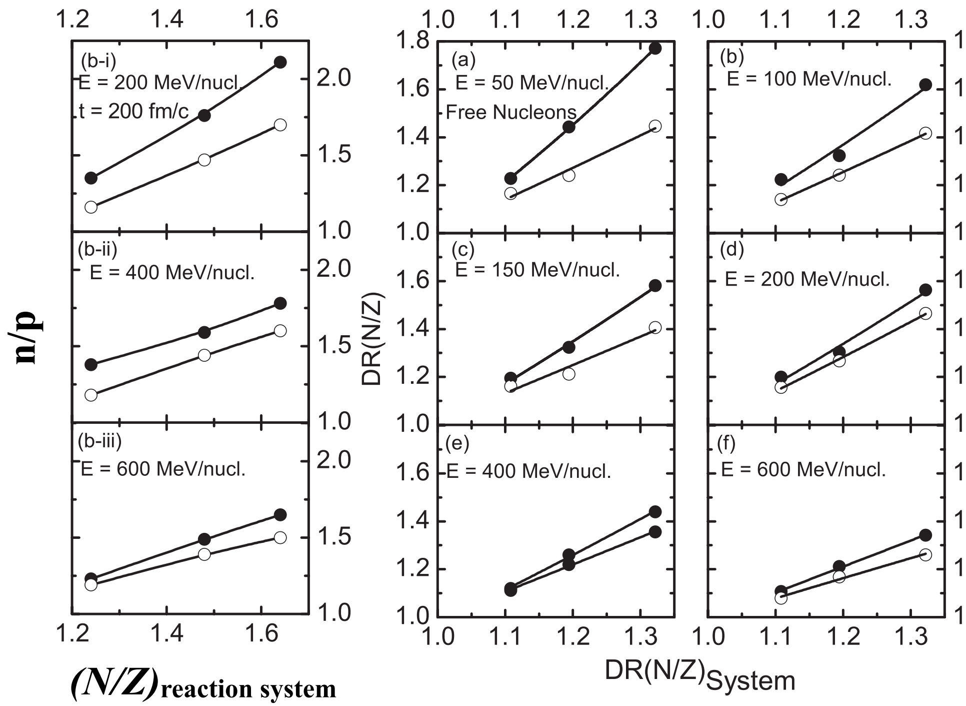
System & Beam Energy Dependence



future RI beam experiments

Z. Xiao *et al.*, PRL 102, 062502(2009)

S. Kumar *et al.*, PRC 85, 024620(2012)



solid = asy-soft
open = asy-stiff

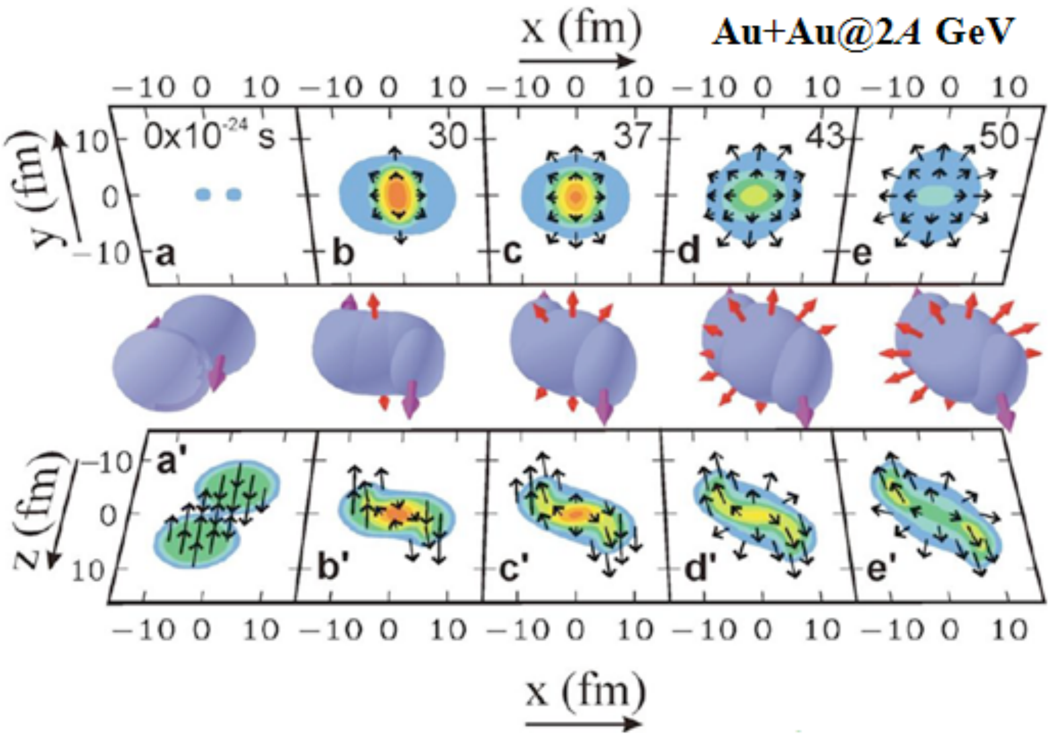
Examples for Sn at RAON
$N/Z(^{106}\text{Sn} + {}^{112}\text{Sn}) = 1.18$
$N/Z(^{132}\text{Sn} + {}^{124}\text{Sn}) = 1.56$

DR(N/Z) = $(N/Z)^{\text{neutron rich}}/(N/Z)^{\text{neutron weak}}$

$N/Z(^{112}\text{Sn} + {}^{112}\text{Sn}) = 1.24$
$N/Z(^{124}\text{Sn} + {}^{124}\text{Sn}) = 1.48$
$N/Z(^{132}\text{Sn} + {}^{132}\text{Sn}) = 1.64$

DR(^{132}Sn/^{124}Sn) = 1.11
DR(^{124}Sn/^{112}Sn) = 1.19
DR(^{132}Sn/^{112}Sn) = 1.32

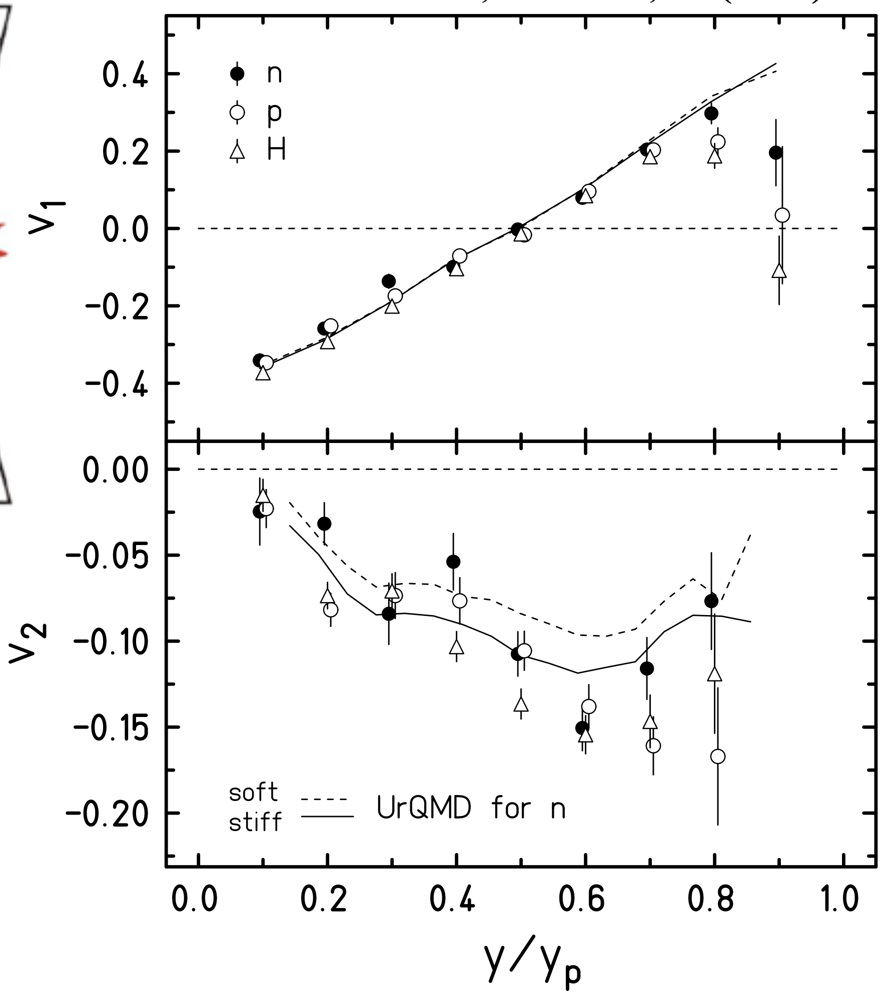
LAMPS Physics Cases



$$E\frac{d^3N}{dp^3} = \frac{d^3N}{2\pi p_t dp_t dy} \cdot (1 + 2v_1 cos(\Phi - \Phi_R^{(n)}) + 2v_2 cos(2 \cdot (\Phi - \Phi_R^{(n)})) + \cdots)$$

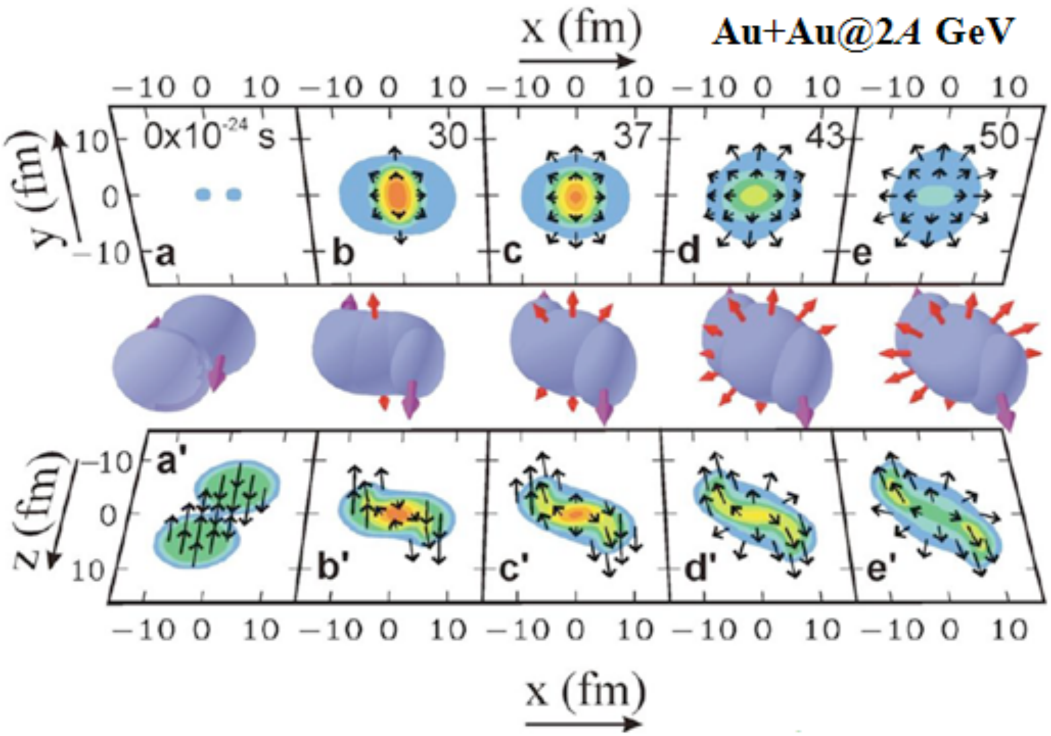
$$v_n = < cos(n \cdot (\Phi - \Phi_R^{(n)})) >$$

P. Russotto *et al.*, EPJA 50, 38 (2014)



Au + Au@ 400*A* MeV
5.5 ≤ b ≤ 7.5 fm, 0.3 ≤ p_t/A ≤ 1.3 GeV/*c*

LAMPS Physics Cases



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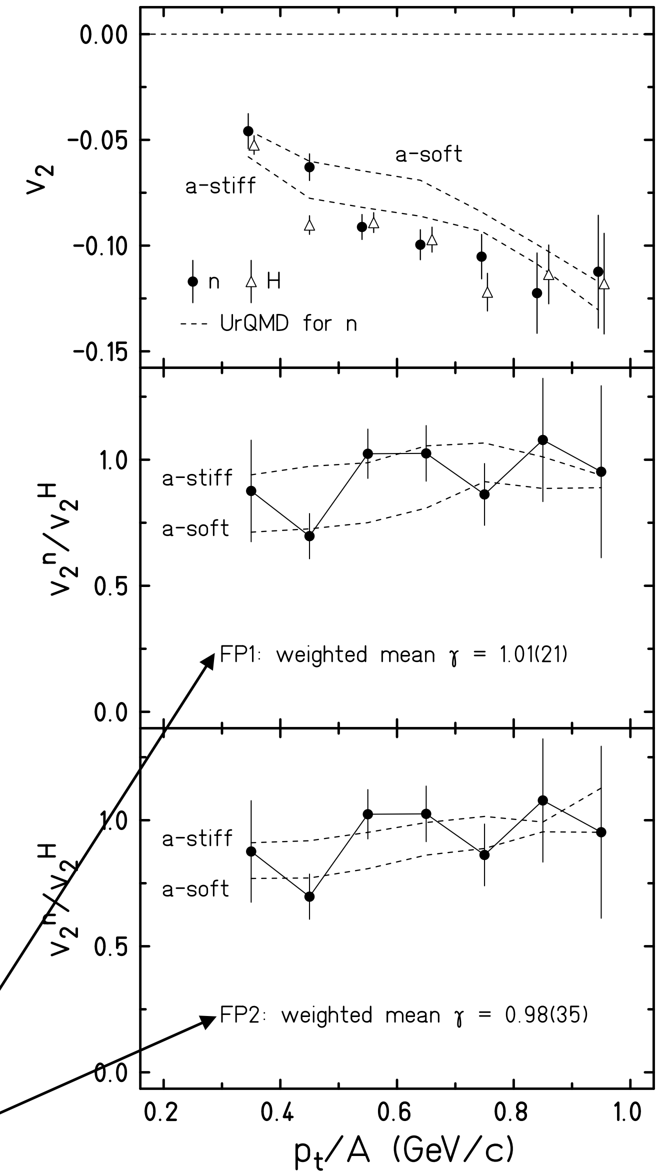


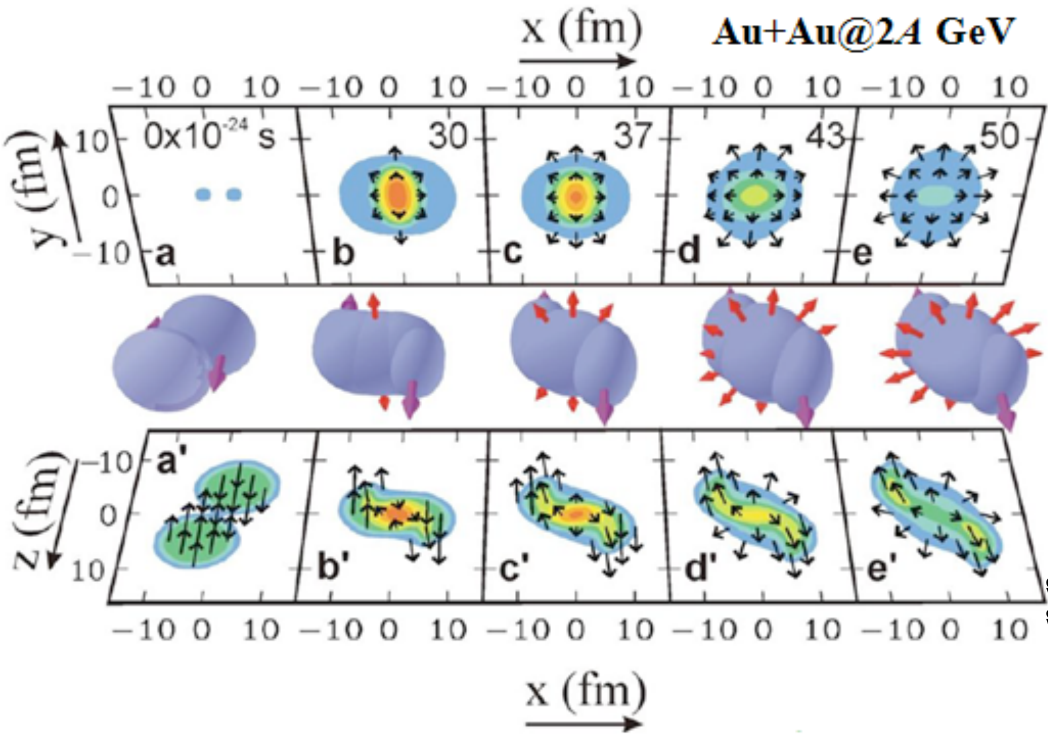
$$E\frac{d^3N}{dp^3} = \frac{d^3N}{2\pi p_t dp_t dy} \cdot (1 + 2v_1 cos(\Phi - \Phi_R^{(n)}) + 2v_2 cos(2 \cdot (\Phi - \Phi_R^{(n)})) + \cdots)$$

$$v_n = < cos(n \cdot (\Phi - \Phi_R^{(n)})) >$$

FP1 & FP2 = different set of the momentum dependence of the elastic nucleon-nucleon cross-section

Au + Au@ 400*A* MeV
b < 7.5 fm, $0.25 \leq y/y_P \leq 0.75$

LAMPS Physics Cases



$$E\frac{d^3N}{dp^3} = \frac{d^3N}{2\pi p_t dp_t dy} \cdot (1 + 2v_1 cos(\Phi - \Phi_R^{(n)}) + 2v_2 cos(2 \cdot (\Phi - \Phi_R^{(n)})) + \cdots)$$

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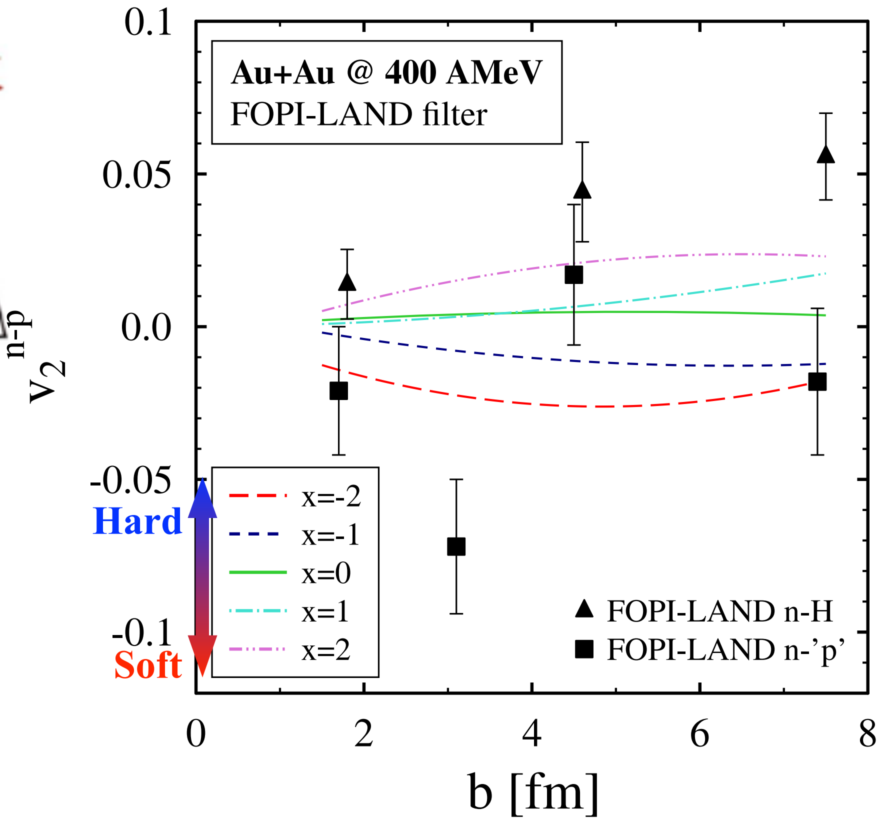
P. Russotto *et al.*, EPJA 50, 38 (2014)



LAMPS Physics Cases

PRL **95,** 132501 (2005) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2005

Evidence for Pygmy and Giant Dipole Resonances in ^{130}Sn and ^{132}Sn

P. Adrich,[1,4] A. Klimkiewicz,[1,4] M. Fallot,[1] K. Boretzky,[1] T. Aumann,[1] D. Cortina-Gil,[5] U. Datta Pramanik,[1] Th. W. Elze,[2] H. Emling,[1] H. Geissel,[1] M. Hellström,[1] K. L. Jones,[1] J. V. Kratz,[3] R. Kulessa,[4] Y. Leifels,[1] C. Nociforo,[3] R. Palit,[2] H. Simon,[1] G. Surówka,[4] K. Sümmerer,[1] and W. Waluś[4]

(LAND-FRS Collaboration)

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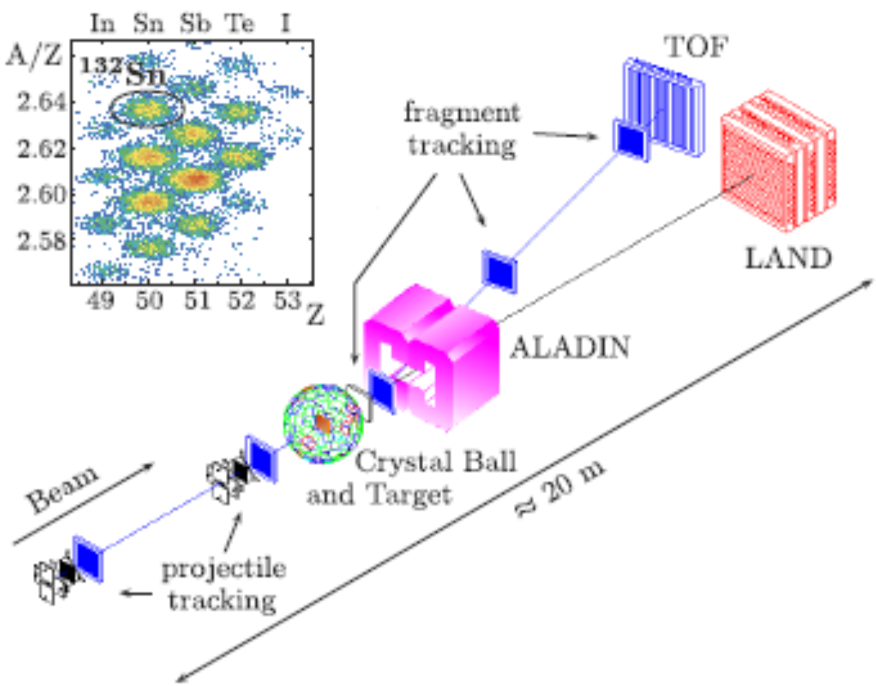
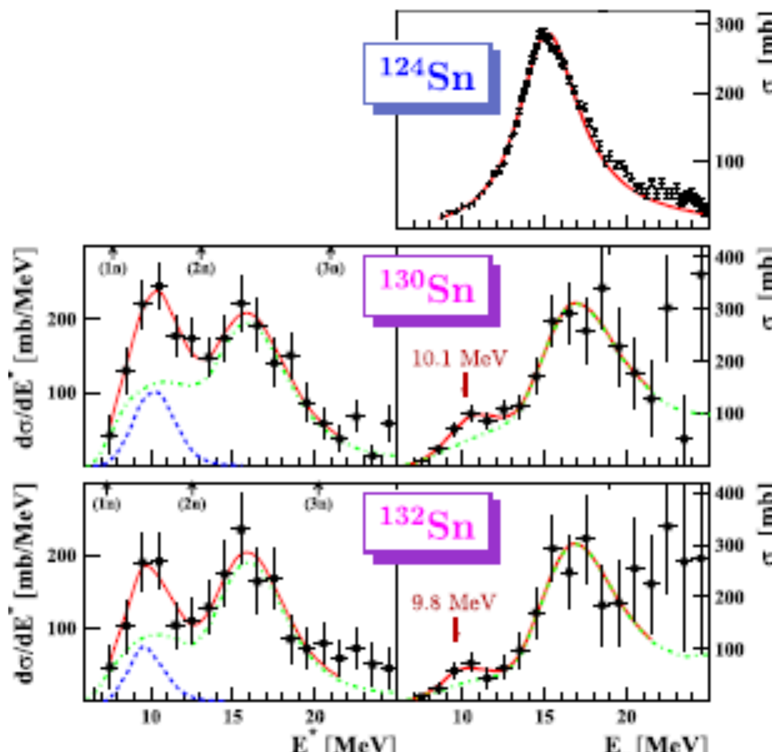
[2]*Institut für Kernphysik, Johann Wolfgang Goethe-Universität, D-60486 Frankfurt am Main, Germany*
[3]*Institut für Kernchemie, Johannes Gutenberg-Universität, D-55099 Mainz, Germany*
[4]*Instytut Fizyki, Uniwersytet Jagielloński, PL-30-059 Kraków, Poland*
[5]*Universidad de Santiago de Compostela, 15706, Santiago de Compostela, Spain*
(Received 29 April 2005; published 21 September 2005)

The dipole strength distribution above the one-neutron separation energy was measured in the unstable ^{130}Sn and the double-magic ^{132}Sn isotopes. The results were deduced from Coulomb dissociation of secondary Sn beams with energies around 500 MeV/nucleon, produced by in-flight fission of a primary ^{238}U beam. In addition to the giant dipole resonance, a resonancelike structure ("pygmy resonance") is observed at a lower excitation energy around 10 MeV exhausting a few percent of the isovector $E1$ energy-weighted sum rule. The results are discussed in the context of a predicted new dipole mode of excess neutrons oscillating out of phase with the core nucleons.



The beam of ^{132}Sn and about 20 other isotopes of similar mass-to-charge (A/Z) ratio were produced by in-flight fission of a ^{238}U primary beam with an intensity of 1.4×10^8 ions/s incident on a Be target. Isotopes were selected according to their magnetic rigidity by the fragment separator FRS [14]. The secondary beams were delivered to the experimental setup with energies around 500 MeV/nucleon. For ^{132}Sn, the intensity amounted to about 10 ions/s on the target. The incoming projectiles were unambiguously identified event by event by determining their magnetic rigidity (with a position measurement in the dispersive midfocal plane of the FRS), time of flight, and energy loss. Projectiles were excited in a secondary ^{208}Pb target (468 mg/cm^2). Additional measurements were performed with a ^{12}C target (370 mg/cm^2) and without target. The results presented in this Letter were deduced from the data effectively collected for 4 days of beam time. The experimental setup and a beam-identification plot are shown in Fig. 1.



Experimental Setup

- We need to accommodate
  - Large acceptance
  - Precise measurement of momentum (or energy) for variety of particle species, including $\pi^{+/-}$ and neutrons, with high efficiency
  - Gamma detection for Pygmy and Giant dipole resonances
  - Keep flexibility for other physics topic

- Beam
  - State beam: p, ^{12}C, ^{40}Ca, ^{58}Ni, ^{96}Ru, ^{96}Zr, ^{112}Sn, ^{132}Xe, ^{158}Au, ^{238}U, and more up to 250 MeV/u
  - RI beam: Ca, Ni, Ru, Zr, Sn, Xe, and more up to 250 MeV/u
    - ✴for commissioning
    - ❖when it is available
    - ❖if it is possible

LAMPS Experimental Setup

RAON

E_{beam} < 250 MeV/u for ^{132}Sn

For Study of Symmetry Energy at Supra-saturation Density via Heavy-Ion Collision Experiments and Nuclear Reaction Study

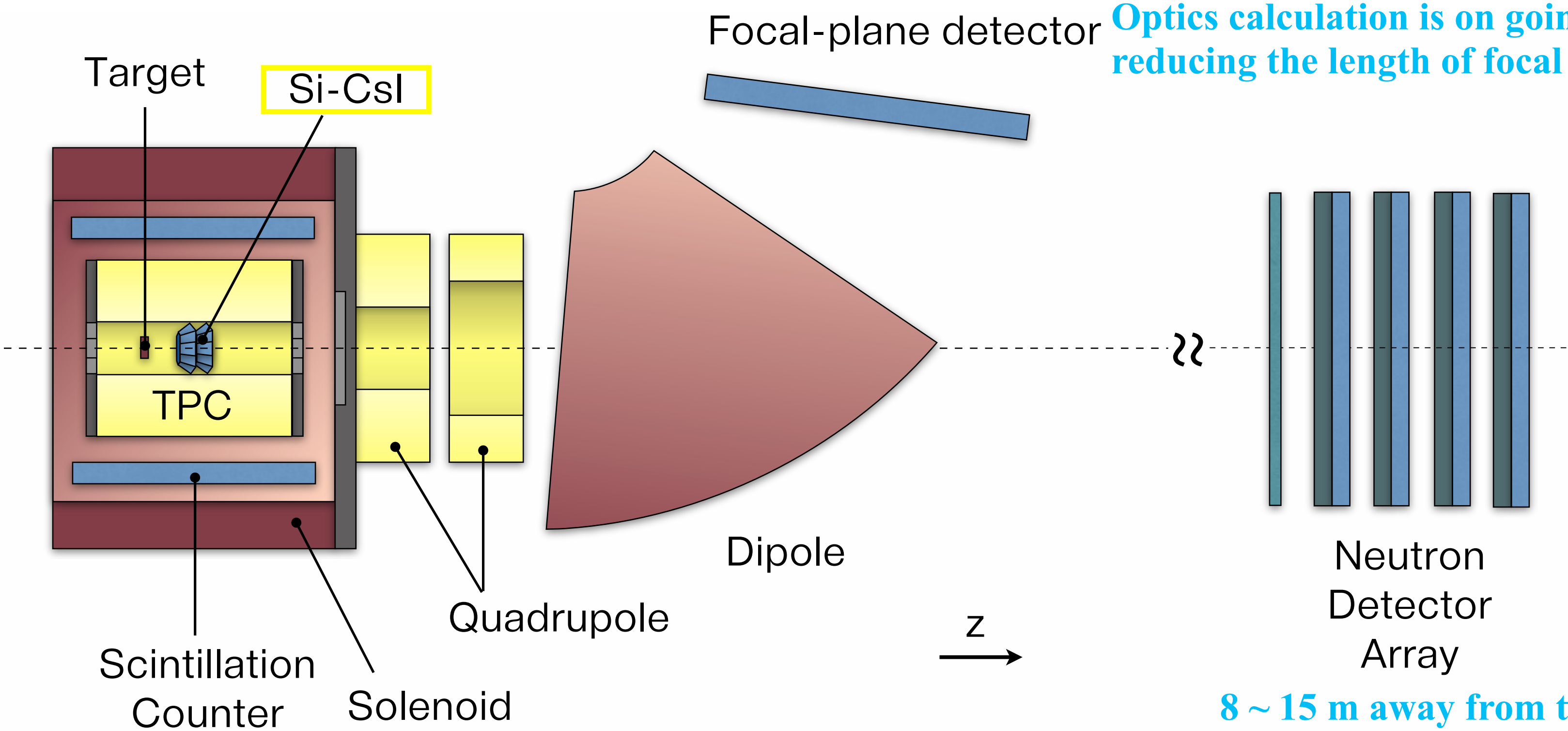
-Example of Reactions for Symmetry Energy Study:

Central and Peripheral Collisions

$^{50,54}Ca + {}^{40}Ca$, $^{68,70,72}Ni + {}^{58}Ni$, $^{106,112,124,130,132}Sn + {}^{112,118,124}Sn$

Si-CsI Array at Solenoid Spectrometer & Dipole Spectrometer are for future upgrade

Optics calculation is on going for reducing the length of focal plane



8 ~ 15 m away from target, movable

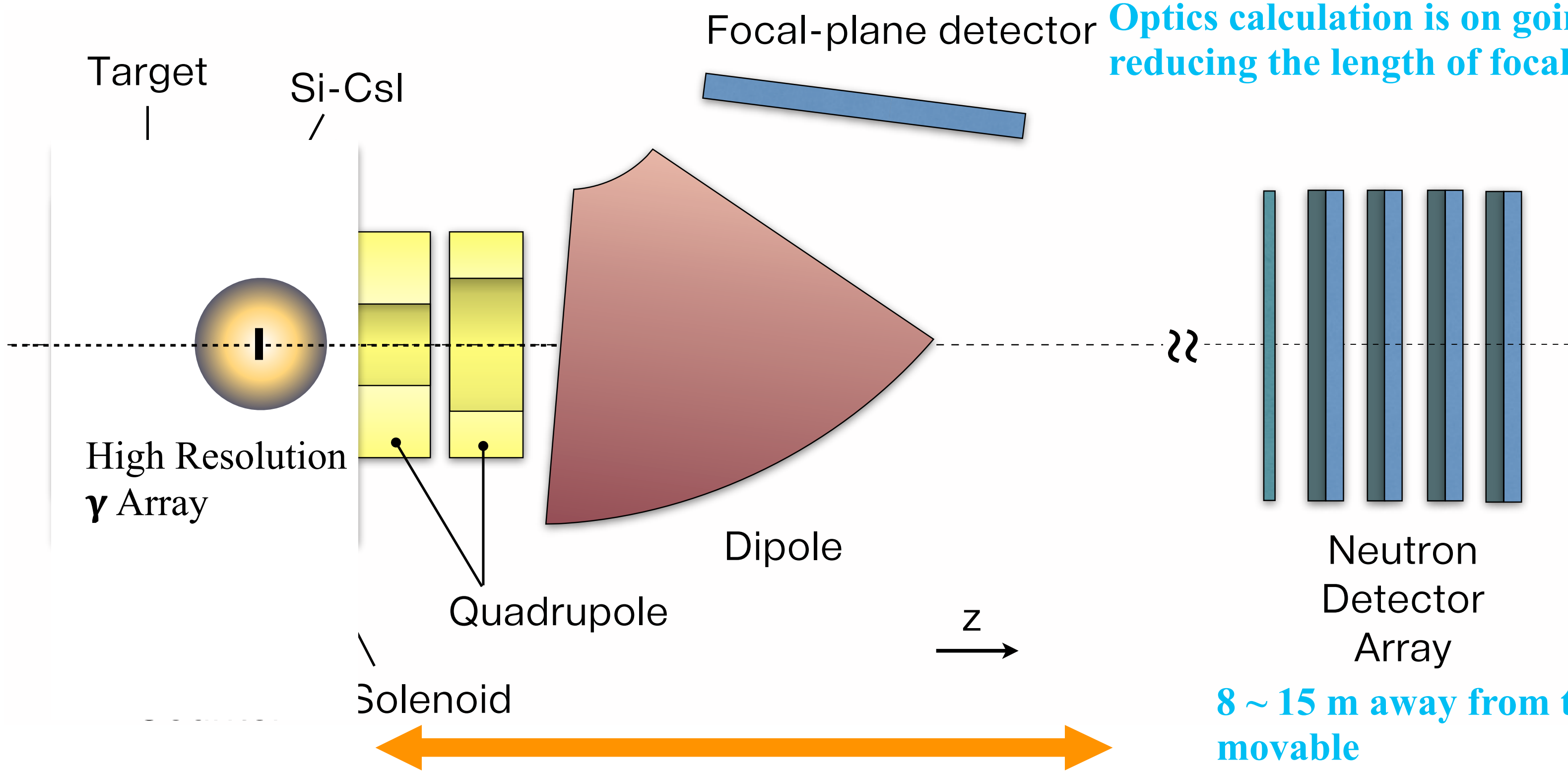
Solenoid Spectrometer

Dipole Spectrometer
(rotatable, Δp = ± 20%, acceptance ≥ 50 msr, Focal plane < 1 m)

Not Scaled

LAMPS Experimental Setup

Other Experimental Configuration



Optics calculation is on going for reducing the length of focal plane

8 ~ 15 m away from target, movable

Dipole Spectrometer
(rotatable, Δp = ± 20%, acceptance ≥ 50 msr, Focal plane < 1 m)

Not Scaled

- GDR/PDR measurements
  - ^{124,130,132}Sn + ^{208}Pb, ^{68,70,72}Ni + ^{208}Pb, ^{50,54,60}Ca + ^{208}Pb, etc
- Photoabsorption measurements
  - Various 1n and 2n removal cross sections for unstable nuclei
- Measurement of E* from gamma, beam fragments, and neutrons

LAMPS Collaboration

- RISP
  - LAMPS Experimental Facility
  - TPC R&D
  - Solenoid Magnet
  - DAQ System

- Adopt & Use
  - TPC GET electronics
  - NARVAL DAQ

- Korea University
  - Neutron Detector and Trigger/ToF Detector R&D
  - TPC Software Development
  - GEANT-4 simulation

- Customized electronics by NOTICE

- Chonbuk National University
  - GEANT-4 simulation
  - Neutron Detector R&D

- Chonnam National University
  - CsI(Tl) detector R&D

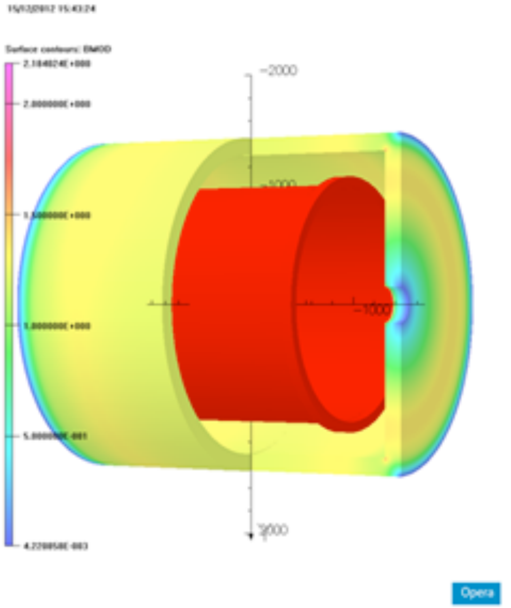
- Kyungpook National University
  - Si detector R&D

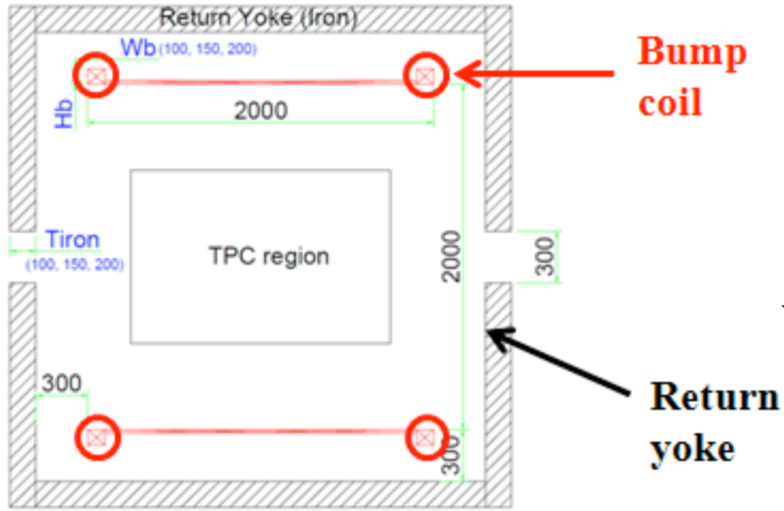
- Inha University
  - TPC tracking algorithm

18 people from 6 domestic institutes

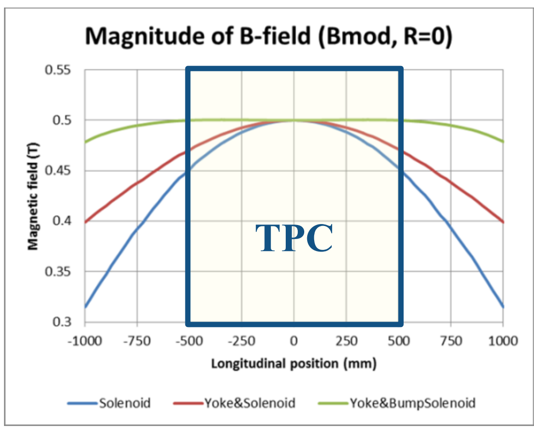
Looking for more collaborators from both domestic and international
➢ To form international collaboration

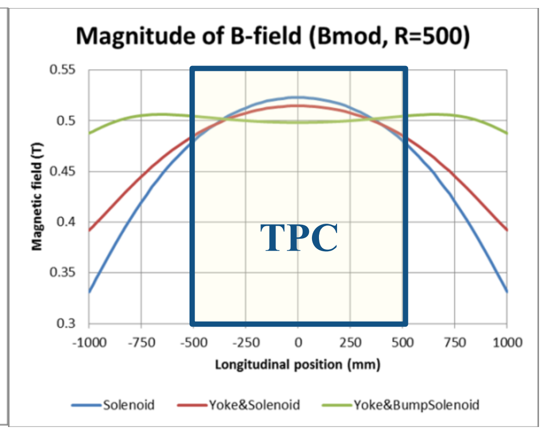
LAMPS Solenoid Magnet





- Cylindrical shape
- Coil: 2 x 2 m^2
- Total size: 3 x 3 m^2
- Boperation: ~ 0.5 T
- Bmax.: ~ 1T
- To cover TPC (r = 0.5 m, l = 1.2 m) with homogeneous B-field
- $\Delta B/B < 2$ %

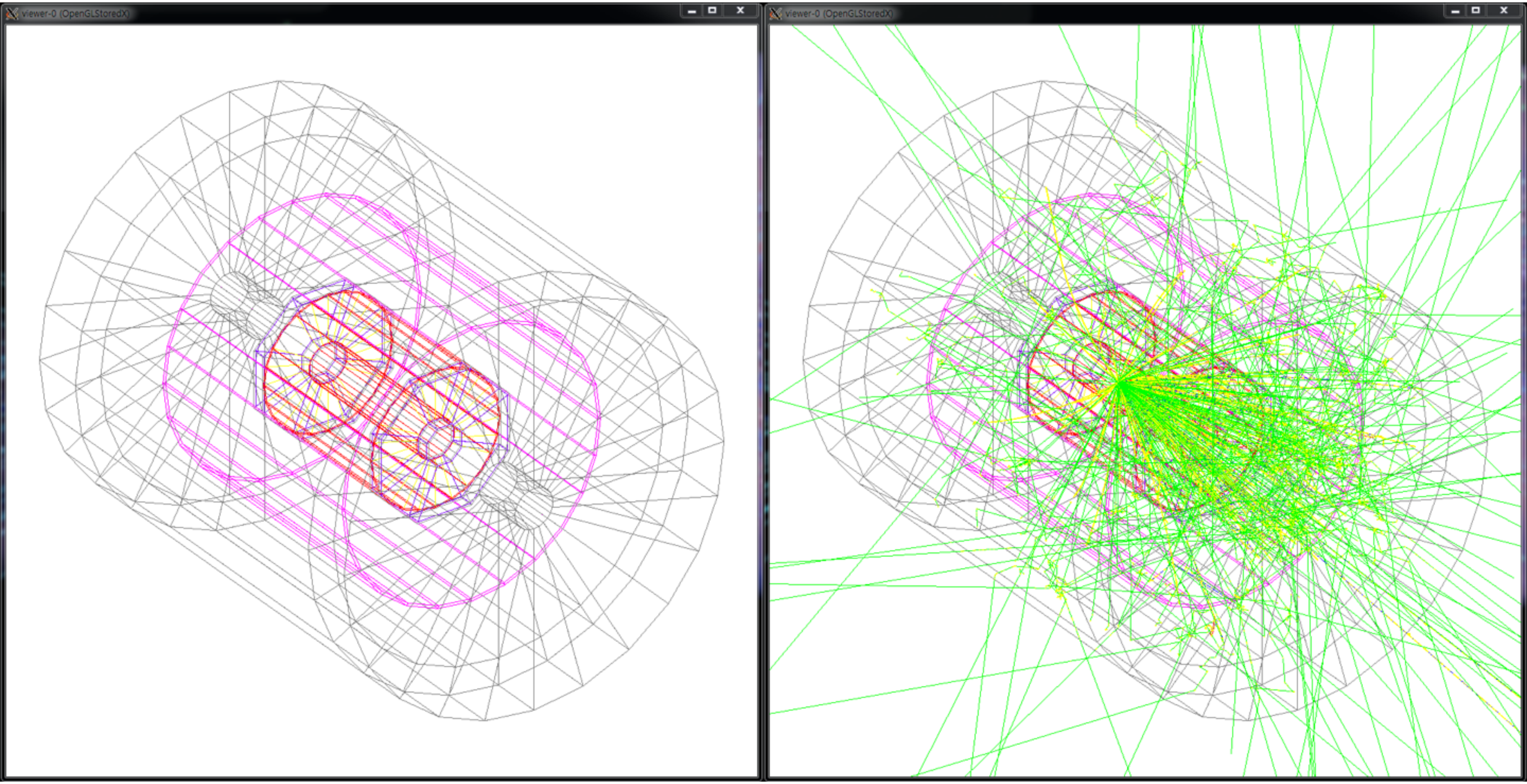




-75 ~ 75 cm	Solenoid Coil	Solenoid with Return Yoke	Solenoid with Return Yoke & Bump Coil
ΔB_{mod} (R = 0 cm)	0.107 T	0.062 T	0.006 T
ΔB_{mod} (R = 50 cm)	0.103 T	0.070 T	0.008 T
ΔB_z (R = 50 cm)	0.110 T	0.072 T	0.008 T
ΔB_r (R = 50 cm)	±0.076 T	±0.043 T	±0.008 T

Two domestic and one foreign magnet product companies express their interests

Neutron Background Simulation Study

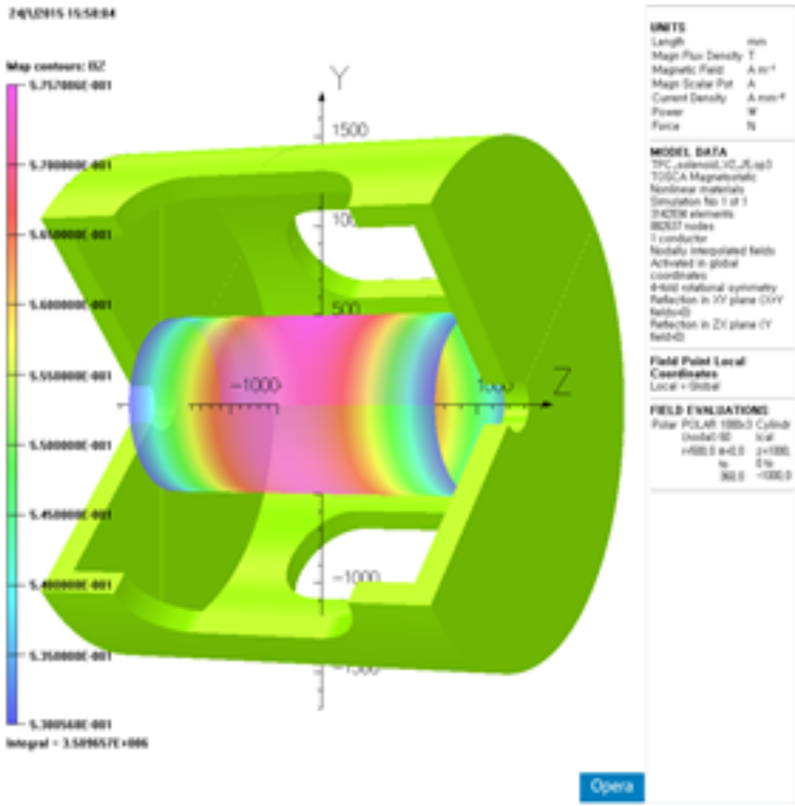


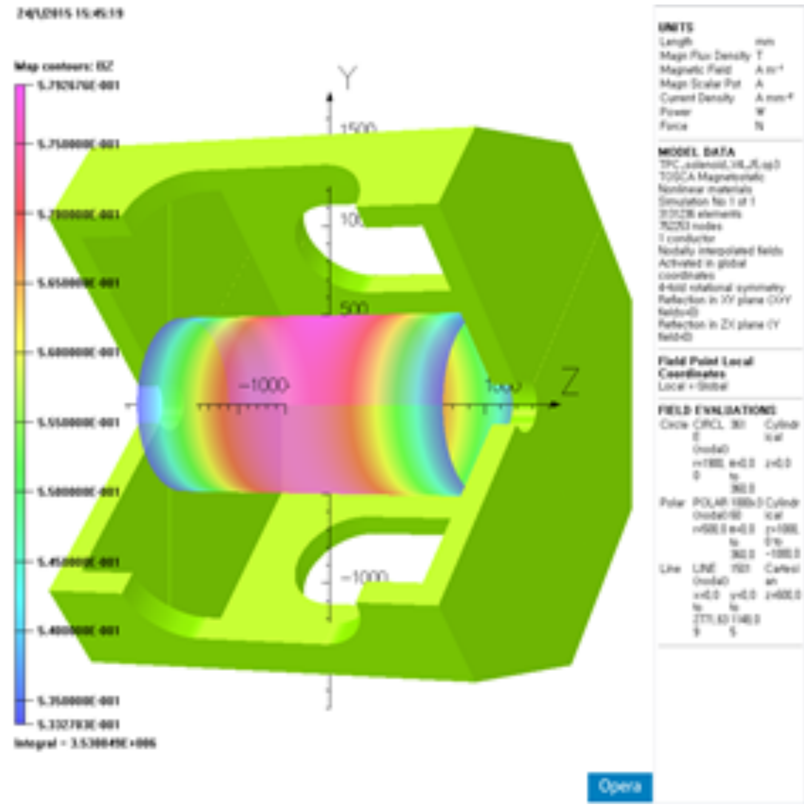
Using IQMD central Au+Au events @ 250*A* MeV (n, p, some IMFs: most harsh case)

➡Varying thickness of return yoke to estimate neutron background →Analysis is in progress

- **Need to check physics package in GEANT4**
- **Will compare with UrQMD (n, p only) & Fluka events**

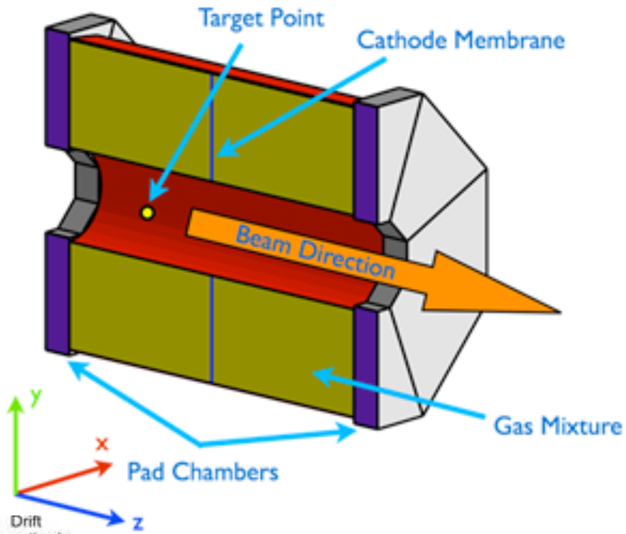
LAMPS Solenoid Magnet

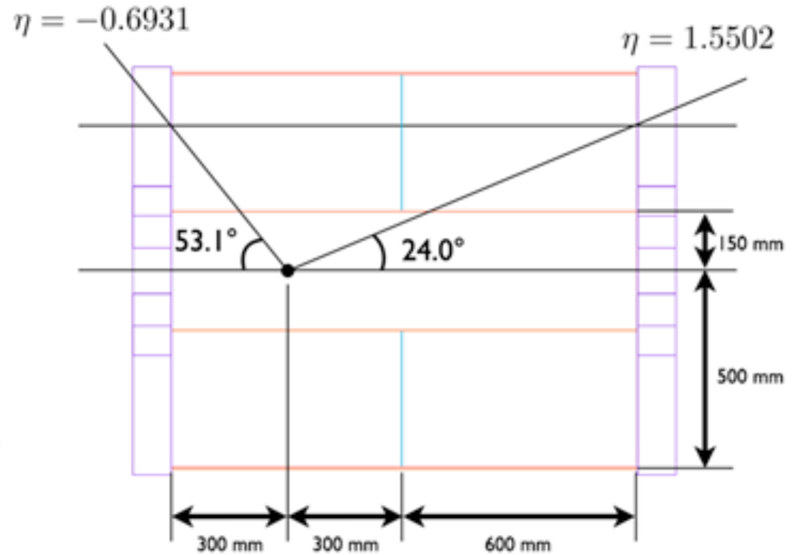


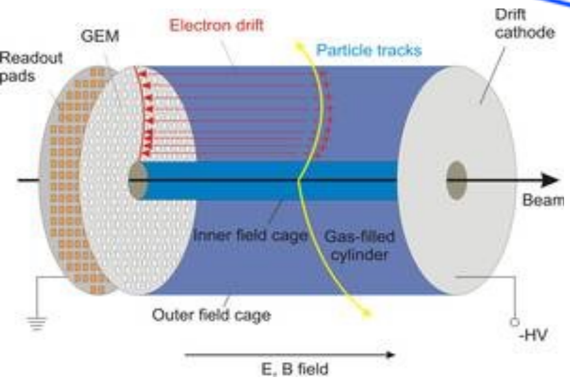


- **Solenoid magnet design is being modified**
  - **For better neutron measurement**
  - **Higher order harmonics occurs but the influence is only < 0.5% in addition to the deviation of magnetic field from previous design**
  - **Further improvement is in progress**
  - **After modification, GEANT-4 simulation is required**

LAMPS Time Projection Chamber (TPC)



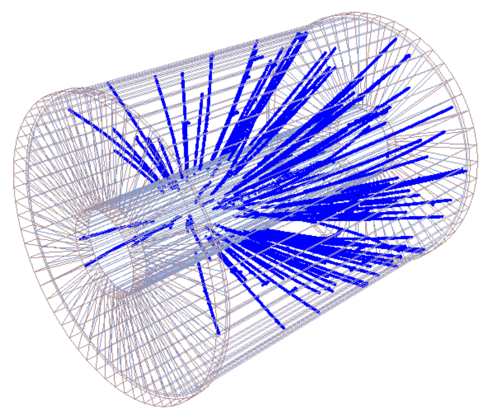


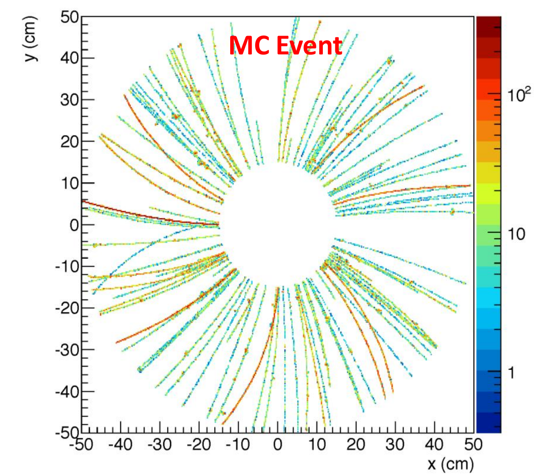


Time Projection Chamber (TPC)

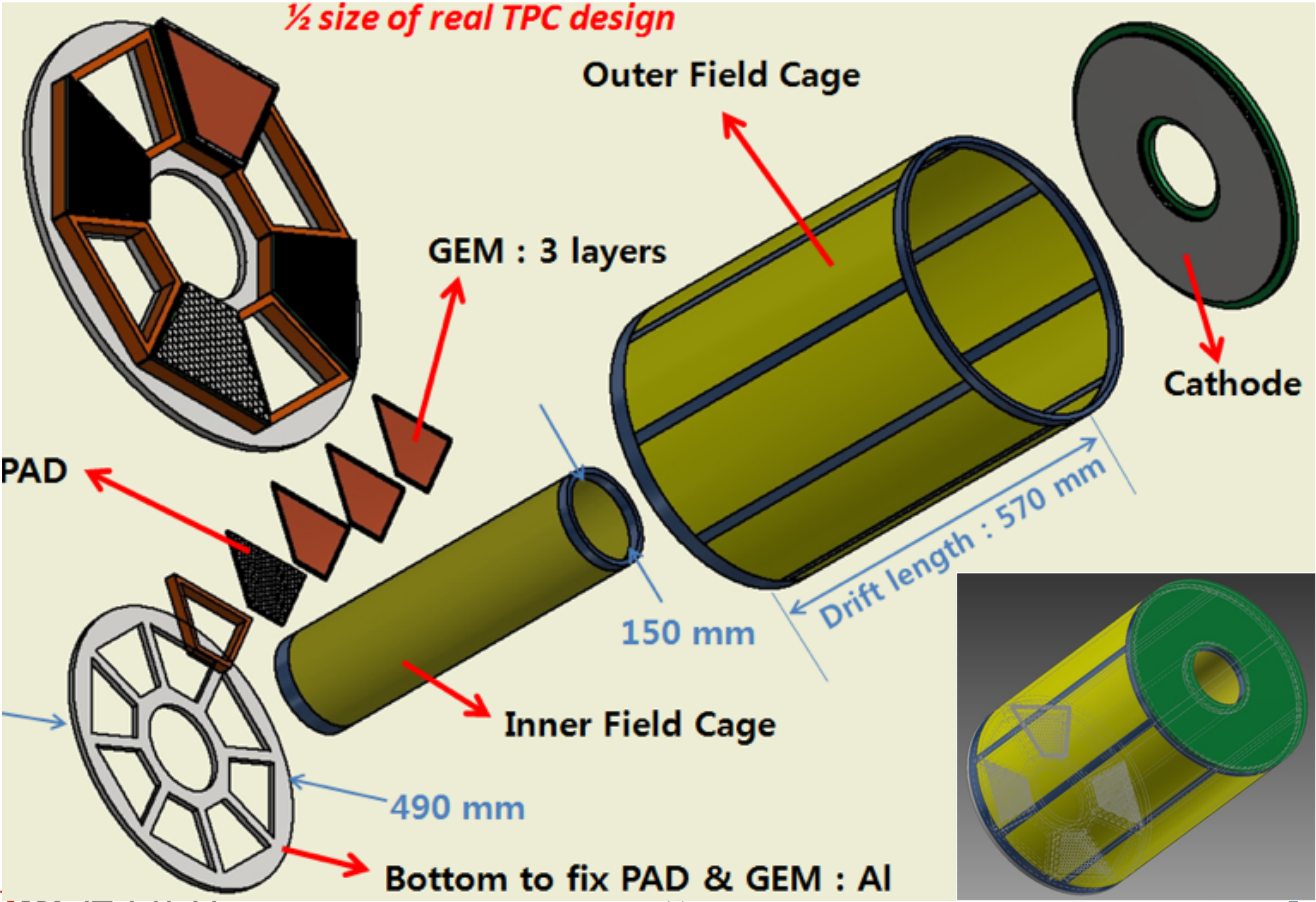
-1 x 1.2 m² cylindrical shape
-Triple GEM based &
pad readout in end-caps
-Large acceptance (~ 3π sr)
★Complete 3D charged particle tracking
➡Particle identification and momentum reconstruction

- IQMD Au+Au @ 250 *A* Mev is used for event generator.
- Gas : Argon (90%) + CO_2 (10%) mixture.
  - Density : 1.78 g/cm³
- Field : 0.5 Tesla





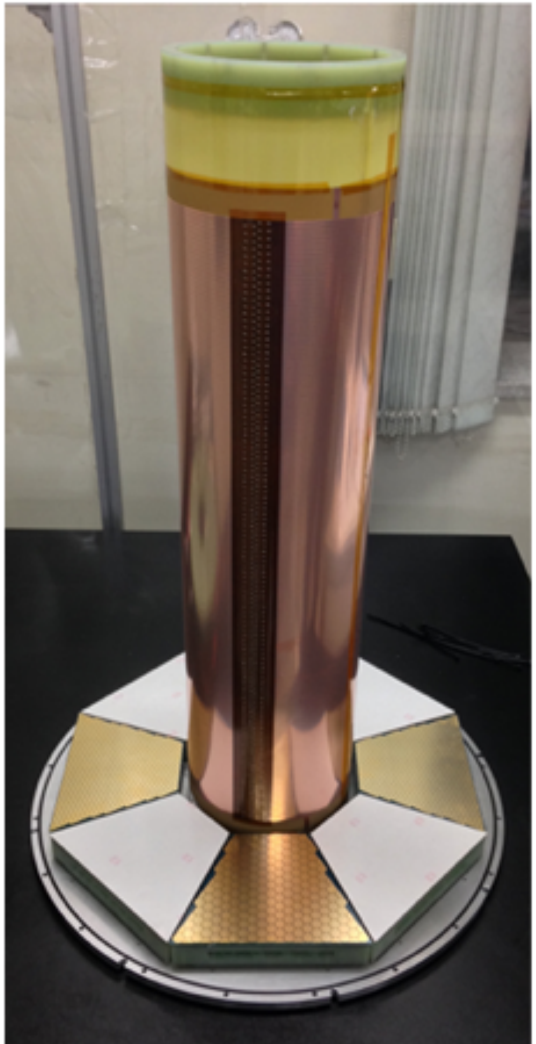
LAMPS TPC Prototype R&D



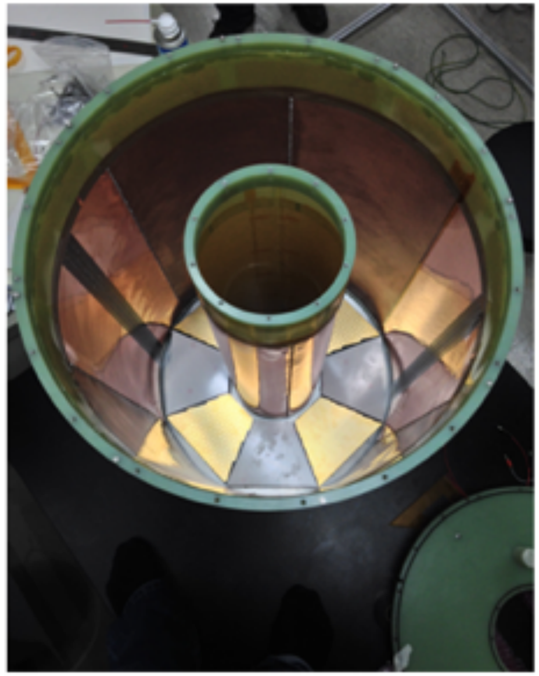
LAMPS TPC R&D

same drift length as final TPC

Inner Field Cage install

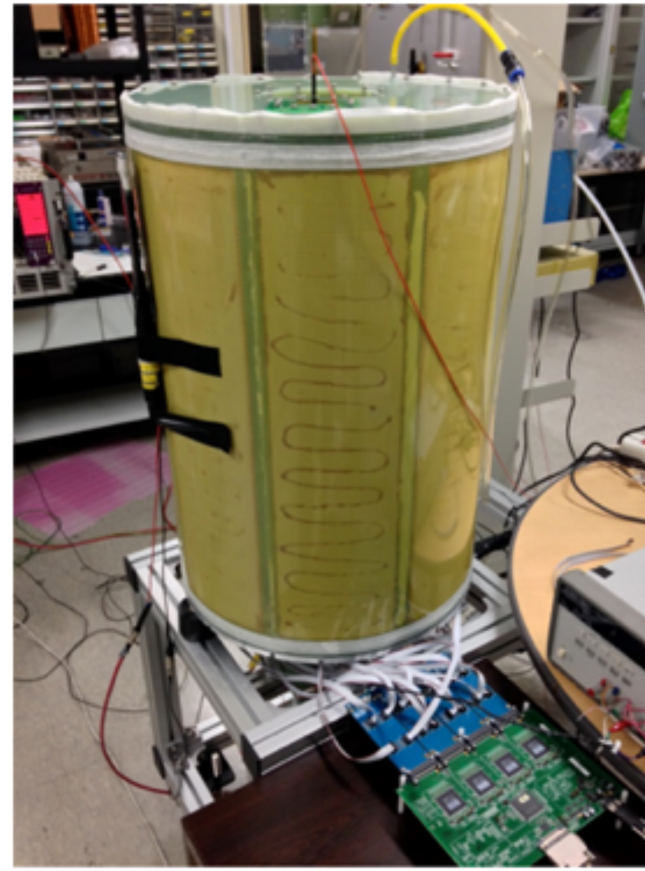


Outer Field Cage install



Prototype TPC : back

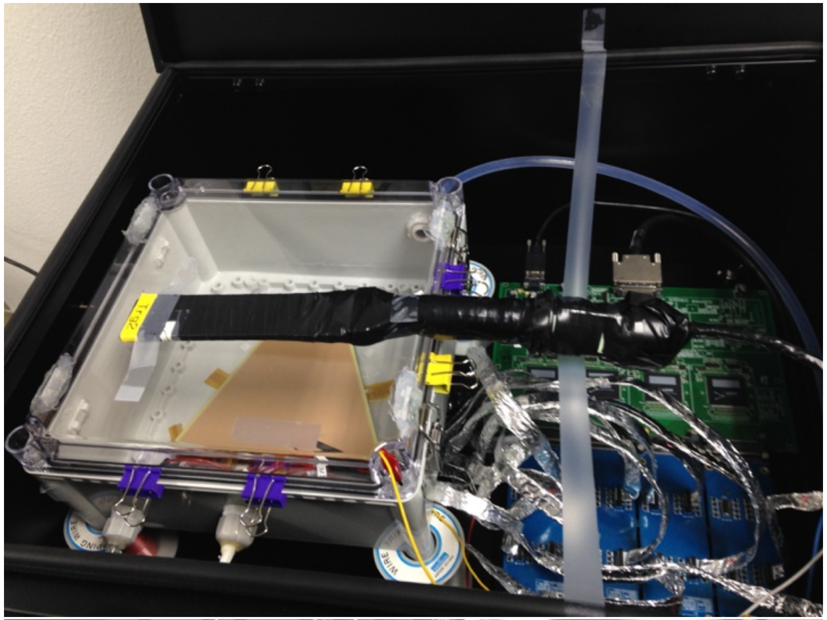
Prototype TPC

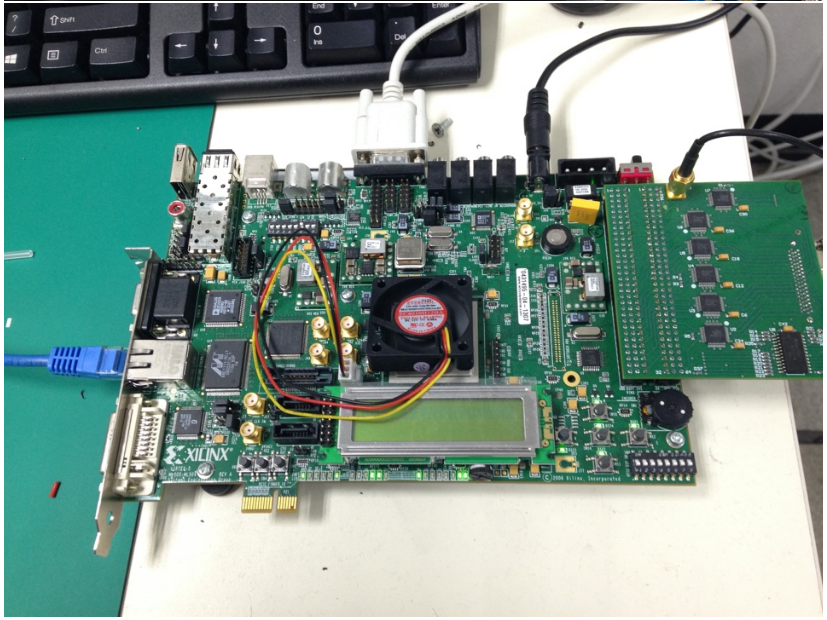


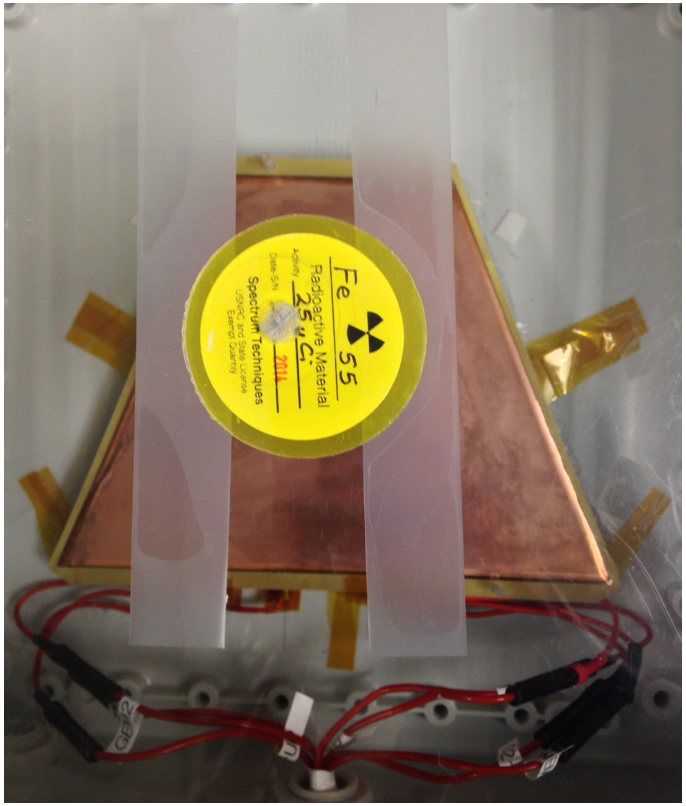
- Problem with GEM foils

-Found new GEM manufacture in Korea (produce GEM foil for CMS upgrade project)

LAMPS TPC GEM Foil R&D





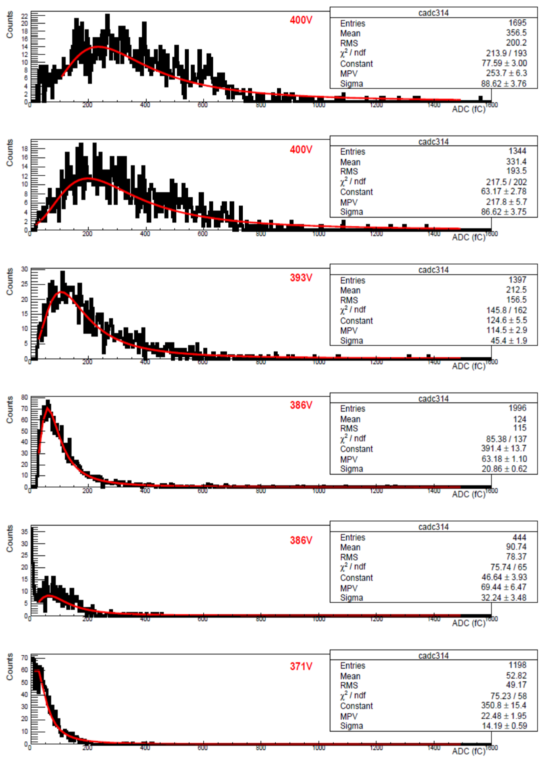


Using cosmic muon & ^{55}Fe source with GET electronics

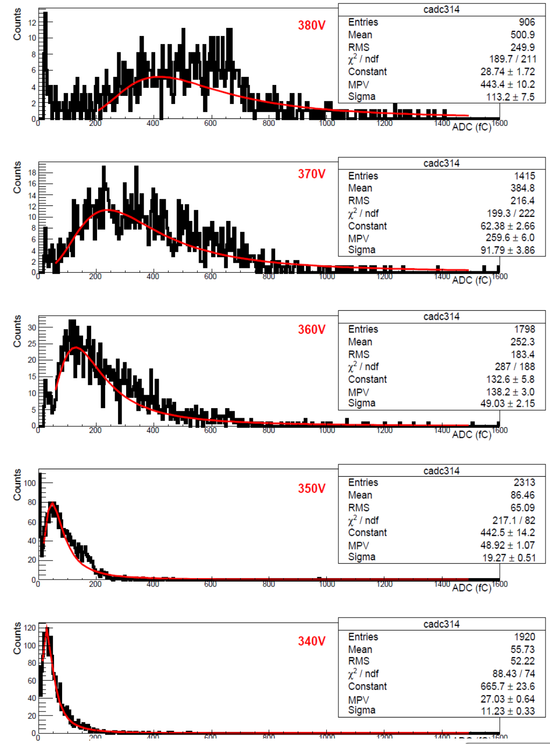
LAMPS TPC GEM Foil R&D

ADC distribution

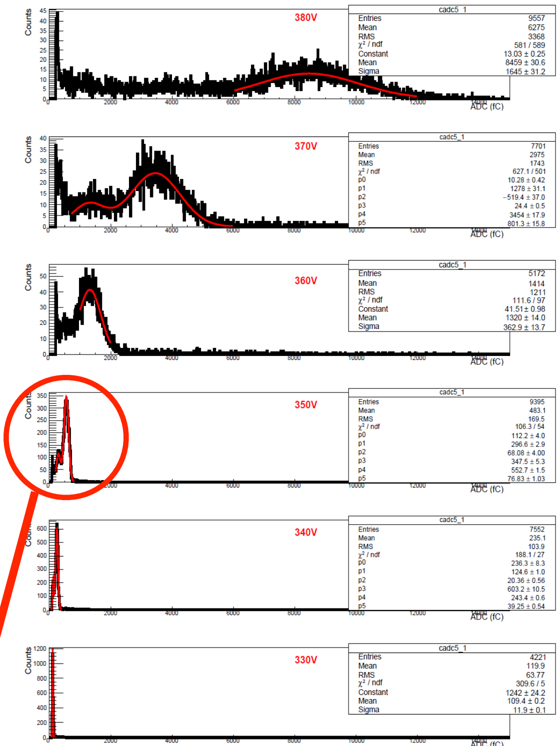
GEM1(UplusLab) - muon

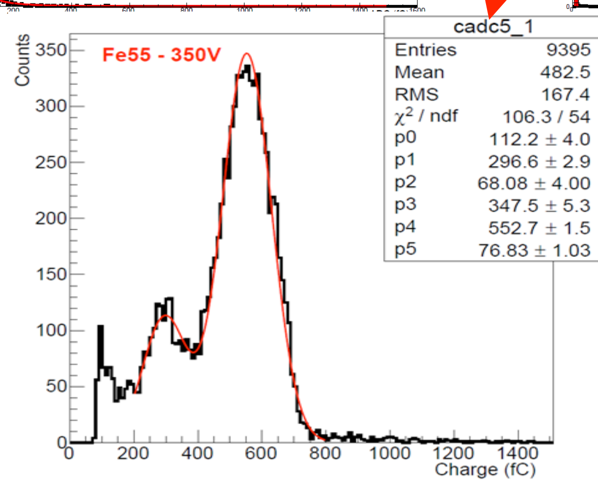


GEM2(Mecharonics) - muon



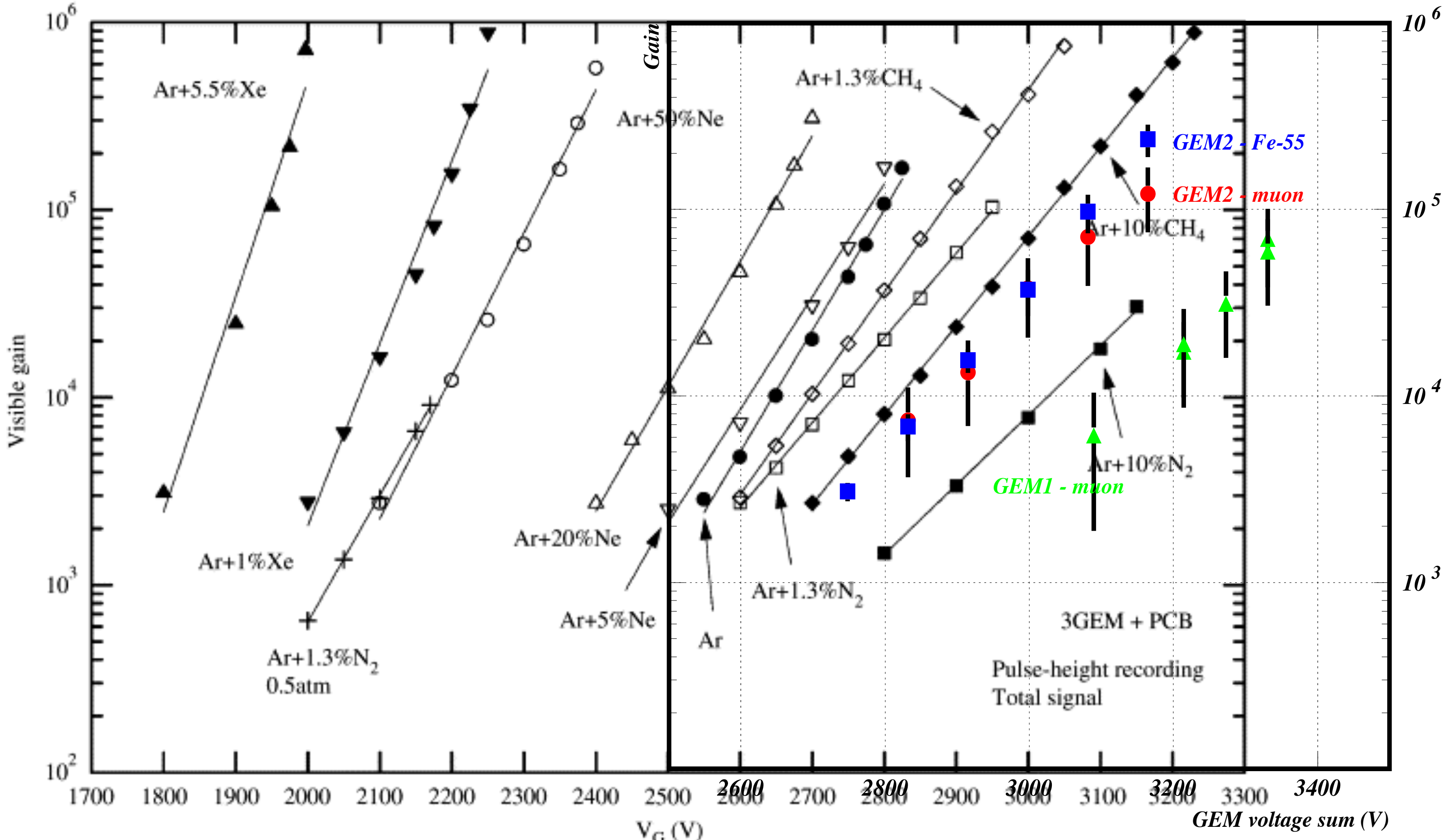
GEM2(Mecharonics) - Fe55





LAMPS TPC GEM Foil R&D

Comparison between data and ref.

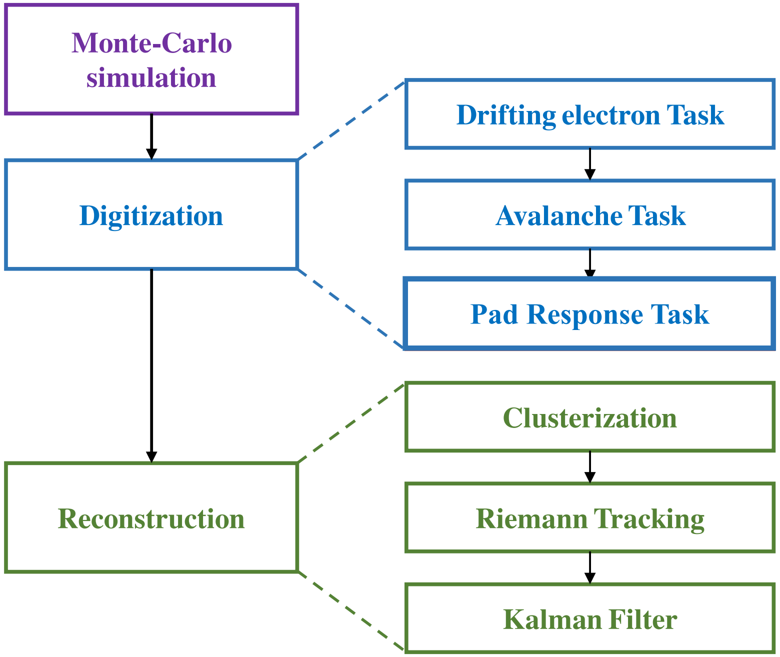


A. Buzulutskov et al.,
NIMA 443(2000) 164

Different test setup and gap distances between GEMs

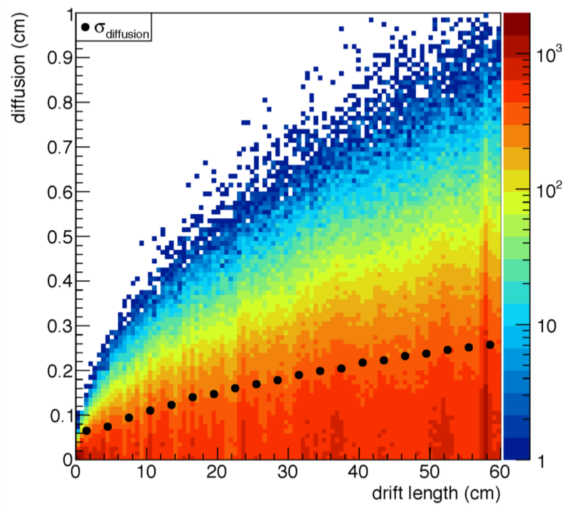
LAMPS TPC Software Development

- **LAMPSROOT is developed based on FAIRROOT.**



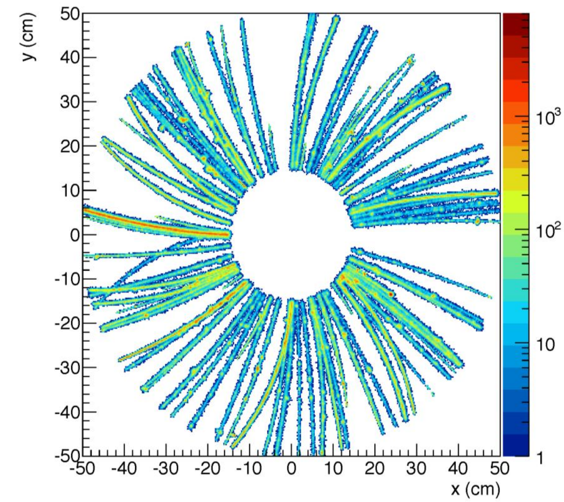
- **Digitization process is developed to simulate ionization, diffusion of electrons and response of GEM and pad.**

Diffusion of electron

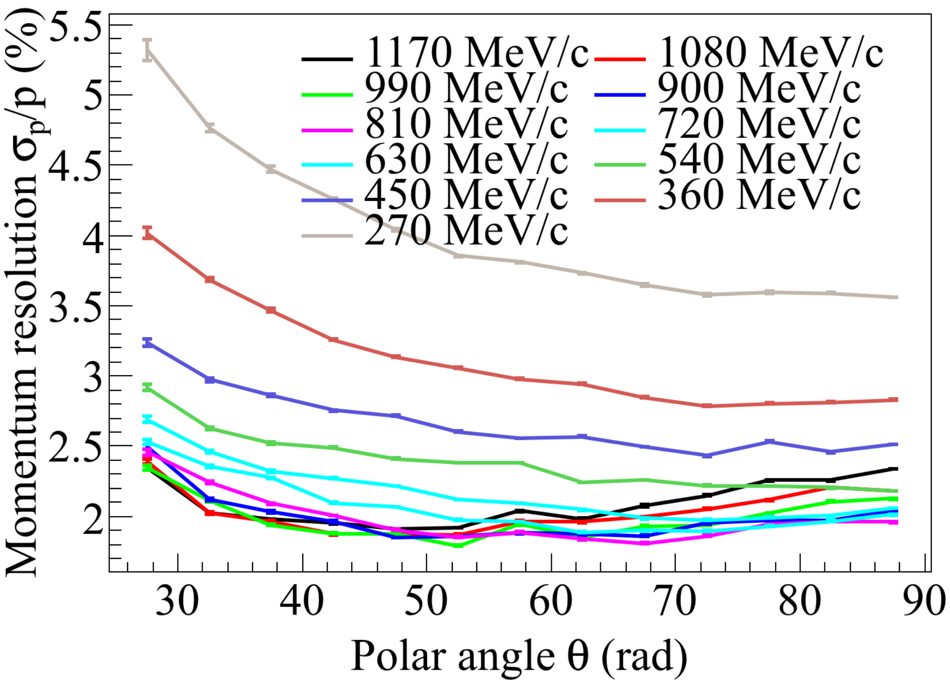


*** Points indicate σ of diffusion**

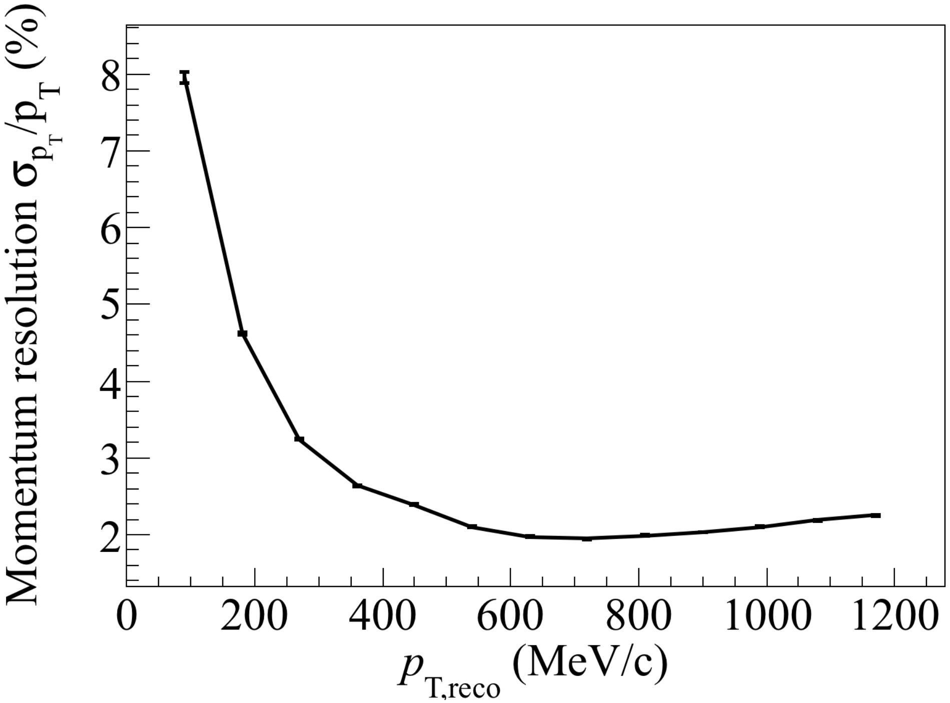
Digitized Event



LAMPS TPC Software Development



Momentum resolution as a function of polar angle
- Proton with different momentum including smearing



Transverse momentum resolution as a function of transverse momentum
- 600 MeV/*c* transverse momentum proton including smearing

readout pad size
inner radius = 3 x 10 mm^2
outer radius = 4 x 15 mm^2

Initial number of readout pad ~ 100k channels

→Aiming to reduce readout channels ~ 50k

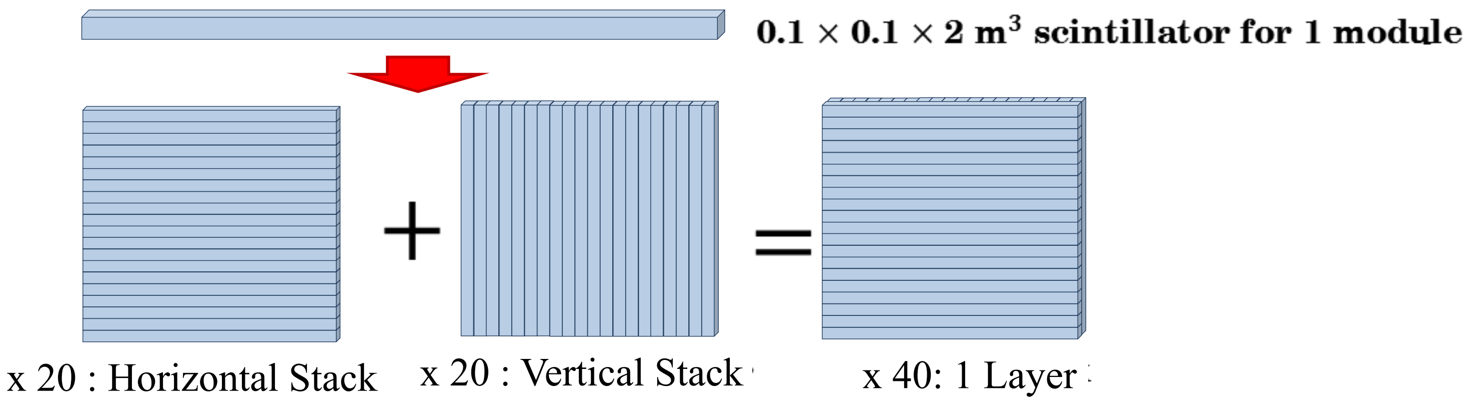
Without any influence for physics measurements, require complete simulation for different design of readout pad to estimate position & momentum resolutions, etc

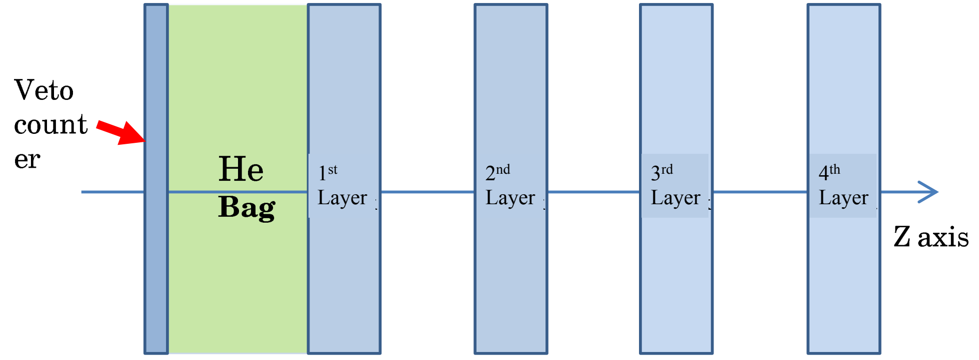
-Working in progress

LAMPS Forward Neutron Detector Array

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

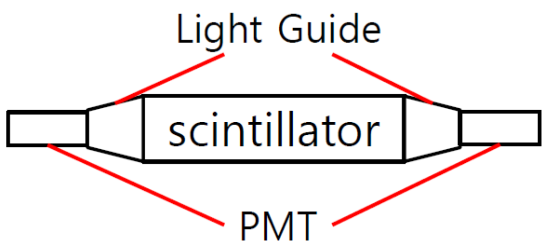
- ✓ Energy range to measure: 30 ~ 300 MeV
- ✓ Time resolution < 500 ps for ToF measurements
- ✓ $\Delta E/E \sim 2 \times 10^{-2}$ via TOF measurements
- ✓ ε = 0.60 for single-neutrons @ maximum 300 MeV (GEANT4)





LAMPS Neutron Detector R&D

Single detector module



- n-p elastic scattering
- n-^{12}C elastic scattering
- $n+p \rightarrow d+\gamma$ (neutron capture, $E_\gamma = 2.23$ MeV)
- $n+^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{C}+\gamma$ (neutron capture, $E_\gamma = 1.2, 3.6, 4.9$ 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

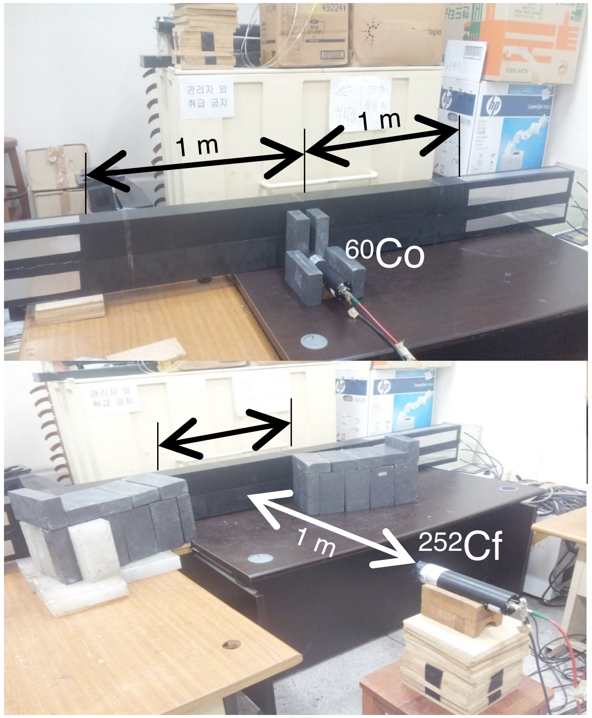
Density: 1.18 g/cm3
Refractive index: 1.4914

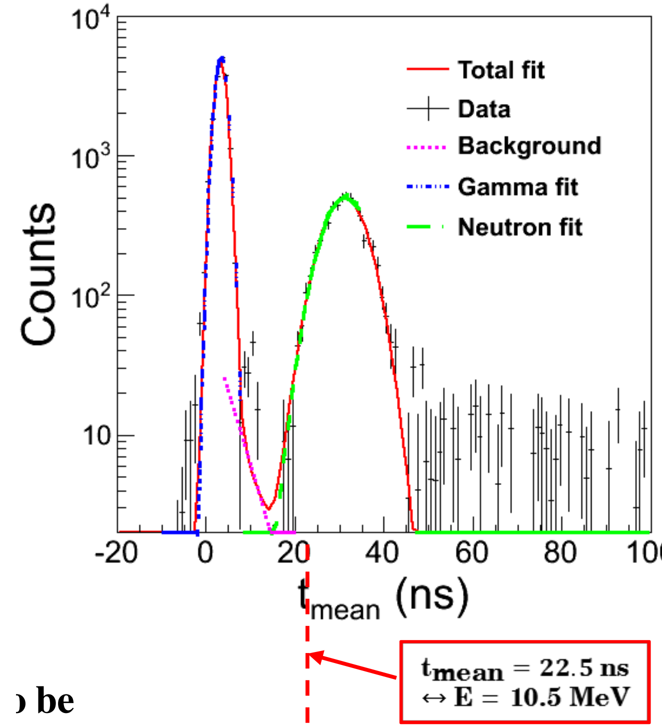
PMT

H2431-50

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

LAMPS Forward Neutron Detector Array R&D

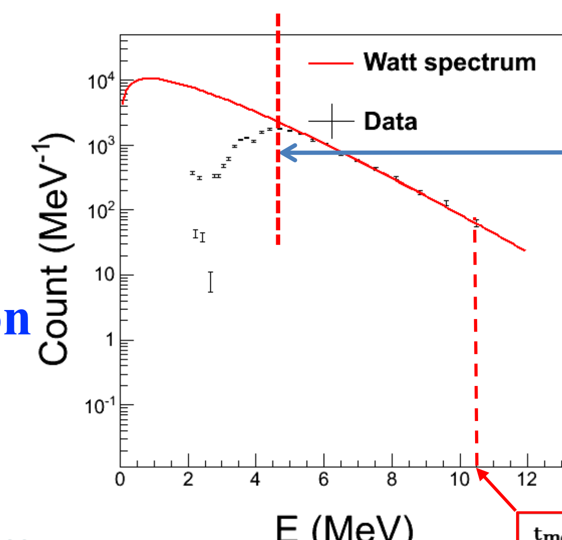




Real size prototypes with commercial electronics are tested with cosmic and radioactive sources

- **-intrinsic time resolution = 392 ps**
- **-position resolution = 6.62 cm**
- **-good separation of gamma and neutron**

Plan to test them again with customized electronics & beam test

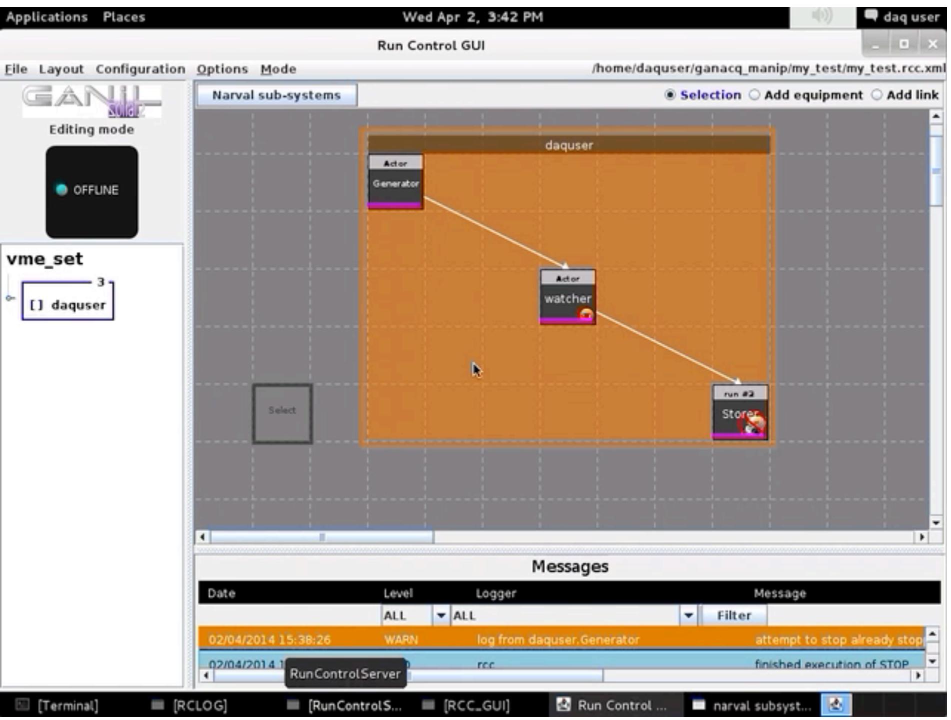


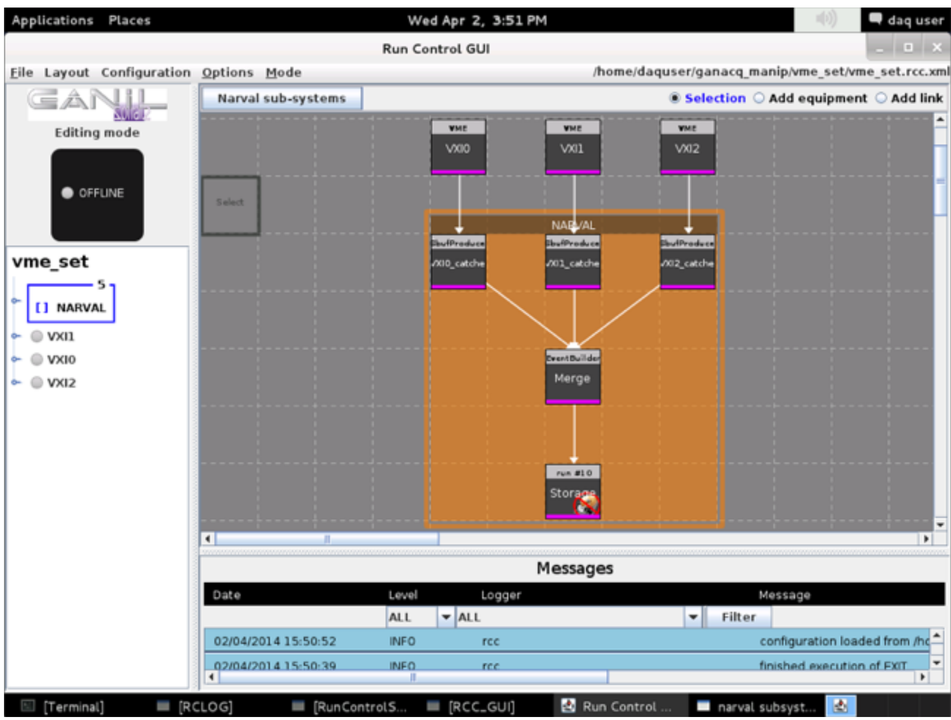
Energy of neutrons to be measured with ε = 0.5 ~ 4.5-MeV

t_{mean} = 22.5 ns ↔ E = 10.5 MeV

LAMPS DAQ System

LAMPS group at RISP develops DAQ based on NARVAL DAQ at GANIL
- **Widely use for nuclear physics experiment**
- **Possibly extending to triggerless DAQ system**
- **Plan to integrate TPC readout (GET system), PMT readout for Neutron & Trigger/ToF detectors (VME)**





Summary

- Large Acceptance Multi-Purpose Spectrometer (LAMPS) at RAON
  - Study of nuclear symmetry energy with RI and stable beam
  - Particle yield, spectrum, ratio, collective flow, and other observables for charged particles and neutron
  - Solenoid spectrometer (solenoid magnet + TPC + plastic scintillators for trigger & ToF + Si-CsI detector※)
    & neutron detector array
    & dipole spectrometer (magnet system + focal plane detector)※
    ※for future upgrade

  ✓To cover entire energy range of RAON with complete event reconstruction within large acceptance
  - Design of experimental setups is almost complete
  - Detector R&D is ongoing
  - Getting more collaborators from not only both domestic and foreign but also nuclear structure
    - Forming international collaboration