9th APCTP-BLTP JINR Joint Workshop at Kazakhstan
"Modern Problems of Nuclear and Elementary Particle Physics"
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Future Opportunity of Nuclear Symmetry Energy at LAMPS/RAON

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(Korea University)

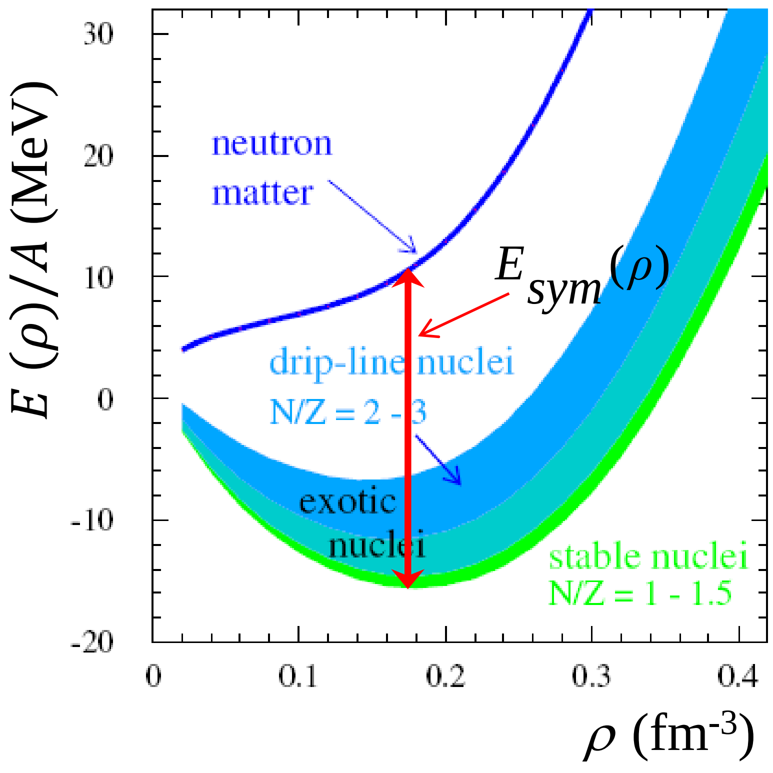
Outline

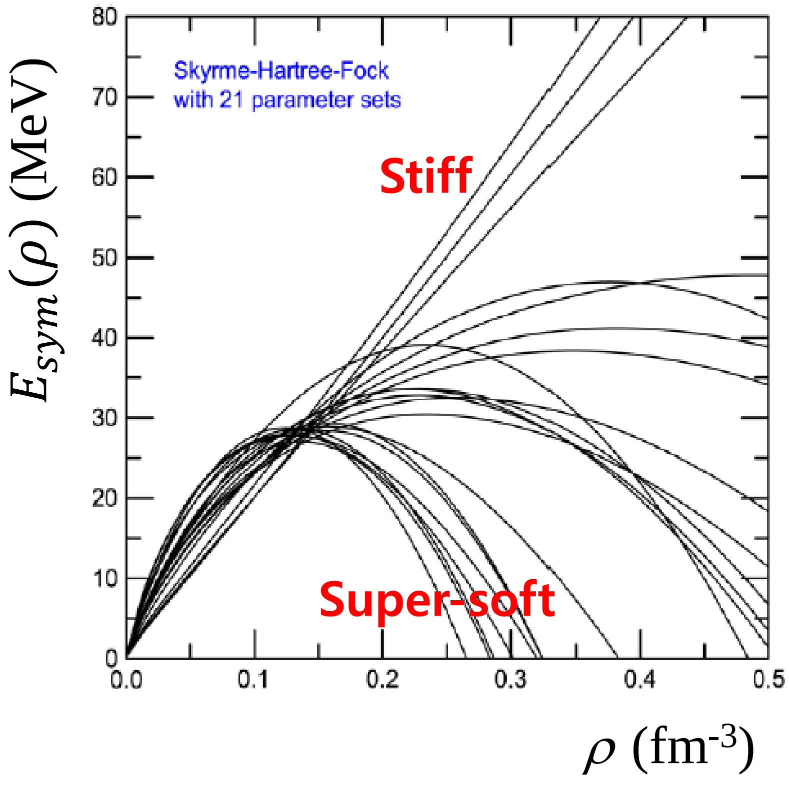
1. Introduction
   – Isospin-dependent dynamics of heavy-ion reactions
   – Interesting observables
2. Experimental setups @ RAON
   – KOBRA: Broad acceptance recoil spectrometer at low energies
   – LAMPS: Large-acceptance multipurpose spectrometer from low to high energies
3. Current R&D efforts
4. Summary

Nuclear EOS & Symmetry Energy

$$E(\rho,\delta)/A = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \cdots$$

with $\rho = \rho_n + \rho_p$ and $\delta = (\rho_n - \rho_p)/\rho$





Nuclear Symmetry Energy

$$E_{sym}(\rho) = \frac{1}{3}\varepsilon_F\,(\rho\,/\rho_0)^{2/3} + E_{sym}^{pot}(\rho)$$

- $E_{sym}^{pot}(\rho)$ is often parametrized as $C(\rho\,/\rho_0)^{\gamma}$
- A useful expansion of $E_{sym}(\rho)$ around ρ_0

$$E_{sym}(\rho) = J + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

where

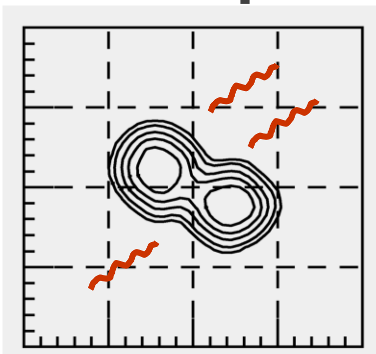
$$L = \frac{3}{\rho_0}P_{sym} = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0} \quad \text{(slope)}$$

$$K_{sym} = 9{\rho_0}^2 \left.\frac{\partial^2\, E_{sym}(\rho)}{\partial \rho^2}\right|_{\rho=\rho_0} \quad \text{(curvature)}$$

Relevant Observables

- Low-energy LAMPS @ ~20 MeV/u
  - Fusion reaction cross section
  - Yield ratio of mirror nuclei
  - N/Z of fragments
    - Charge equilibration/Isospin mixing/Neck fragmentation
  - Dipole emission
    - Yield & polar angle dependence
- High-energy LAMPS @ >200 MeV/u
  - Yield ratio of mirror nuclei
  - Isospin diffusion parameter
  - Collective flow
  - π^-/π^+ ratio
  - Dipole emission

Dipole Emission in Fusion

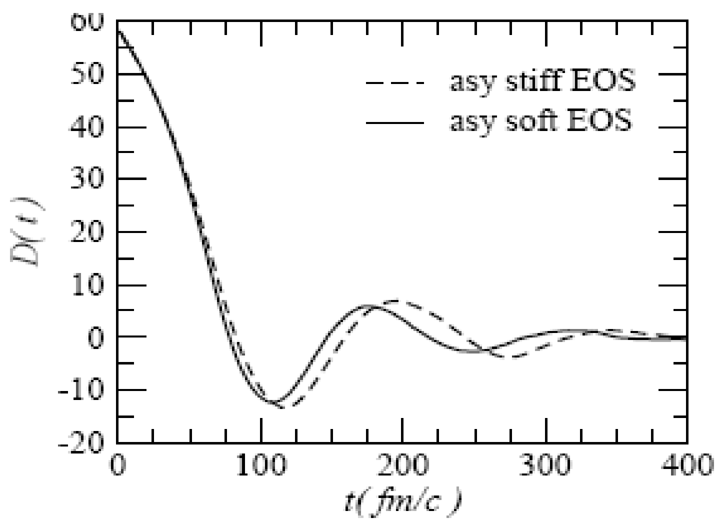


$N_1/Z_1 \neq N_2/Z_2$

C. Rizzo et al., PRC 83, 014604 (2011): SMF

- The charge oscillation in fusion radiates collective dipole bremsstrahlung γ's during the isospin equilibration process.
  - Relative position of CM's for n & p: $$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right]$$

$^{132}Sn + ^{58}Ni$ at 10 MeV



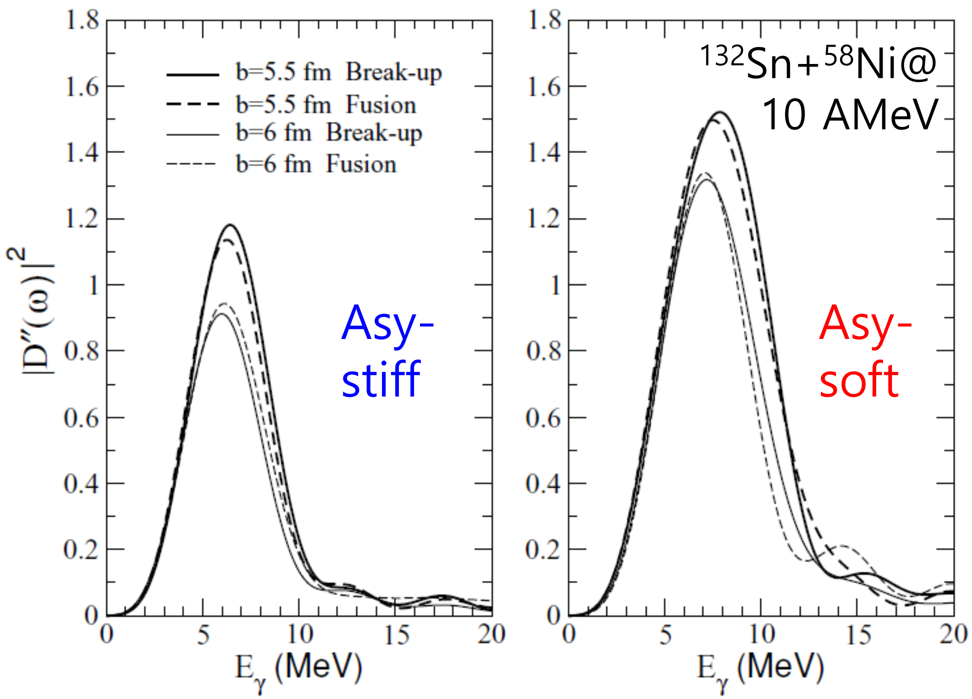
- Photon emission probability with $E_\gamma = \hbar\omega$

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|D''(\omega)\right|^2$$

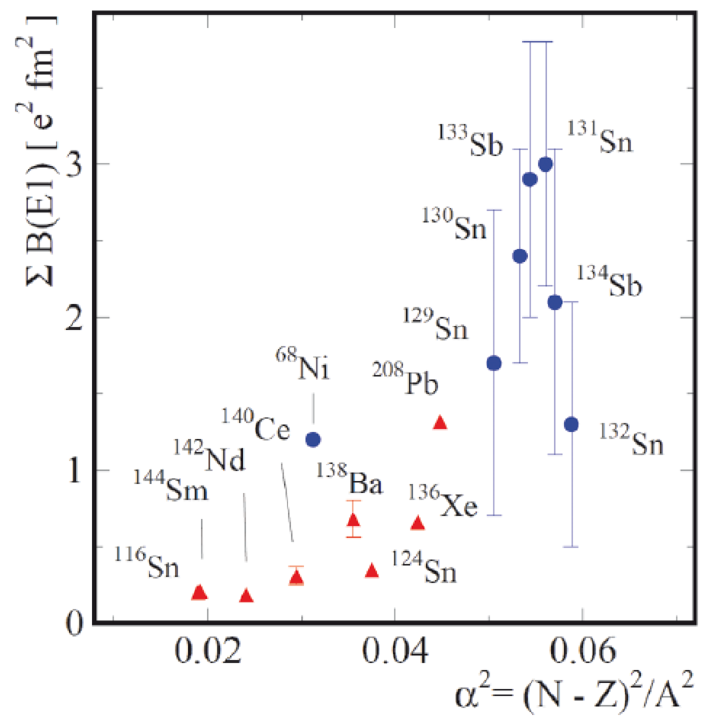
- Similar effect in (ID)QMD model [Wu et al., PRC81, 047602 (2010)]

Dipole Emission in Fusion

C. Rizzo et al., PRC 83, 014604 (2011)



A. Klimkiewicz et al. (LAND), PRC 76, 051603 (2007)



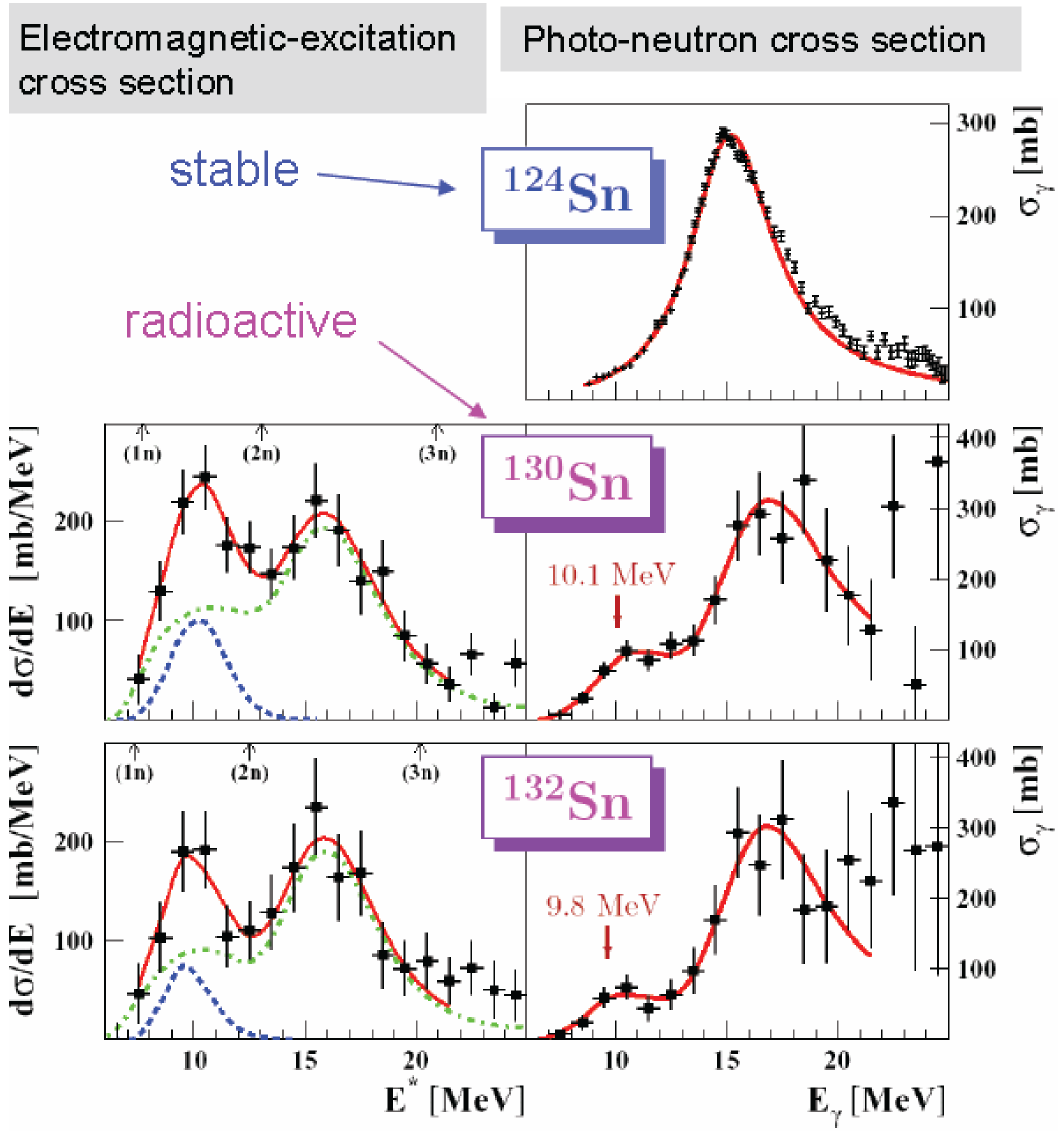
- More γ emission for Asy-soft
  - Fusion ≈ Breakup
  - The strength increases with the isospin asymmetry

Dipole Response at High Energies

FRS Expt. @ GSI
$^{124,130,132}Sn + ^{208}Pb$
@ 500 AMeV

- Coulomb excitations of n-rich $^{130,132}Sn$ isotopes reveal peaks at ~10 MeV (PDR)
  - Absent for stable ^{124}Sn isotope

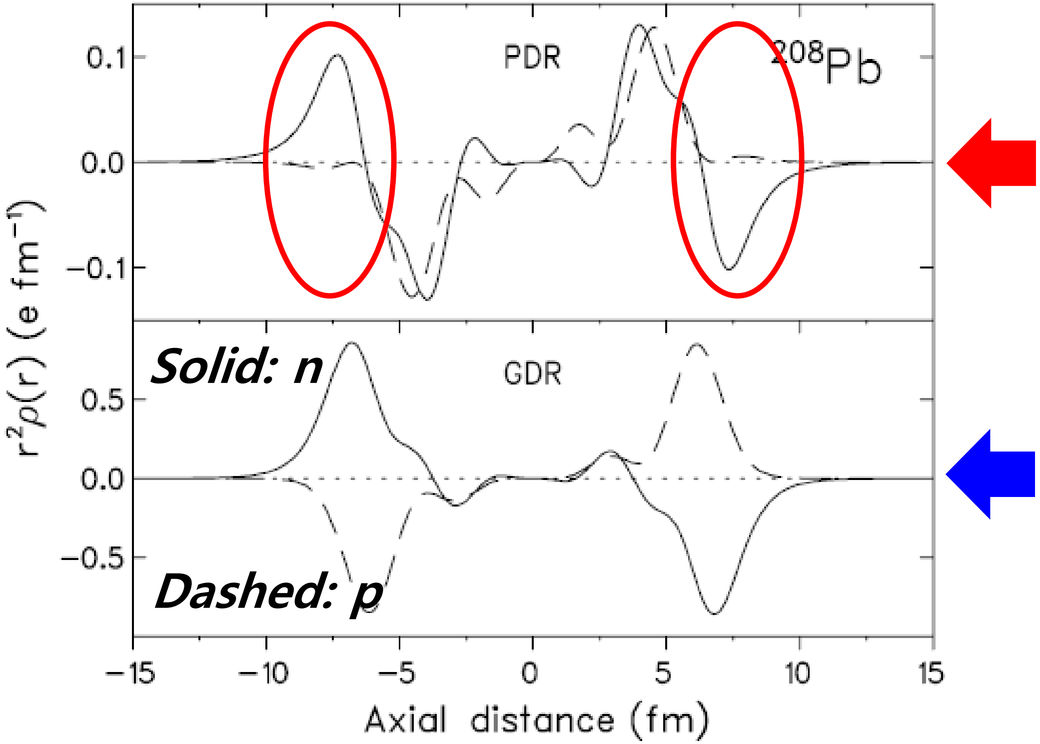
P. Adrich et al., PRL 95, 132501 (2005)



Dipole Response of n-Rich Nuclei

N. Ryezayeva et al., PRL 89, 272502 (2002)

Microscopic quasiparticle phonon model

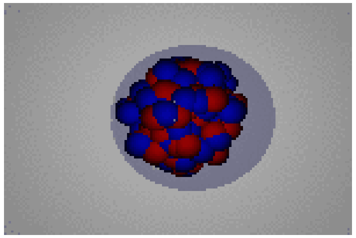


Interior: n & p move in phase (IS)

Surface: only neutrons contribute

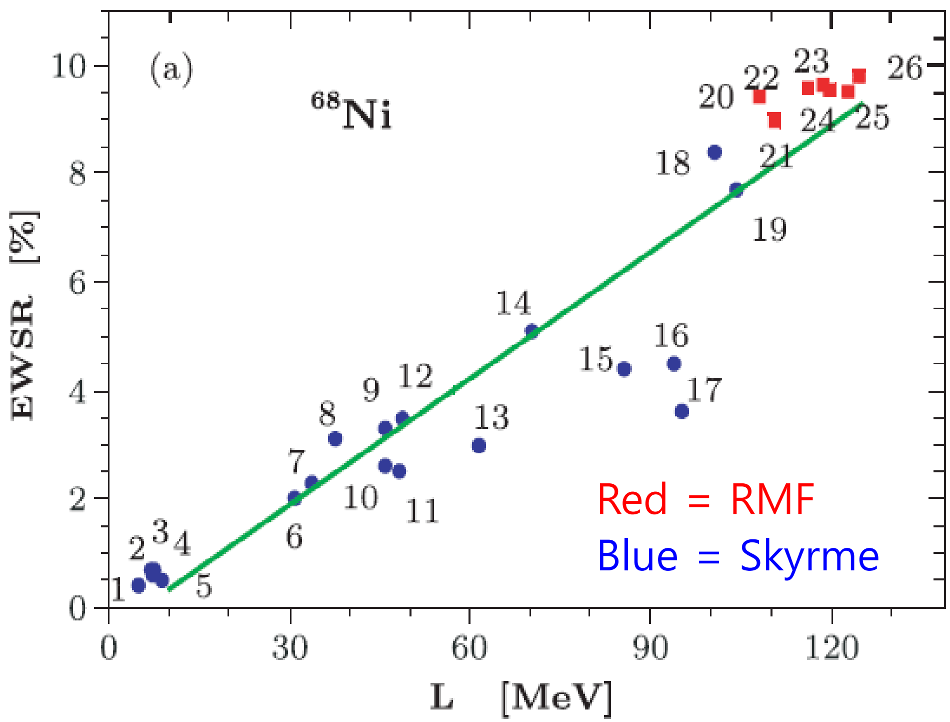
n-p oscillates out of phase (IV)

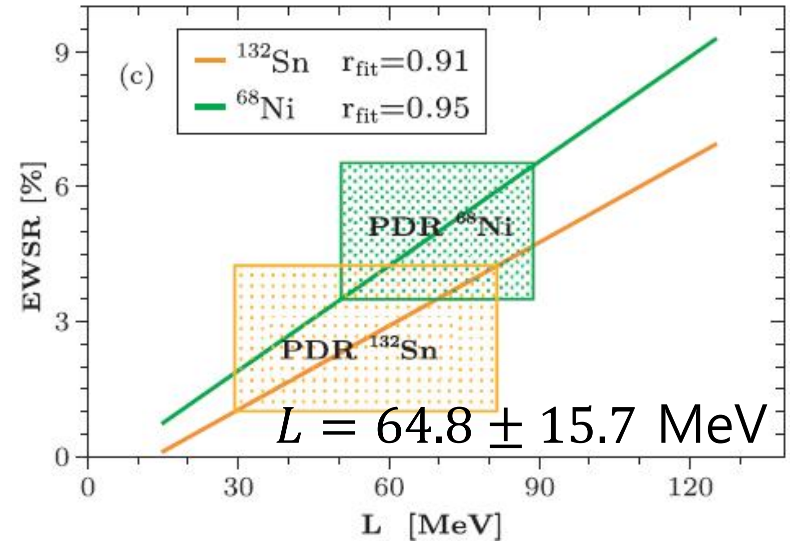
- Pygmy dipole resonance (PDR) can be interpreted as an oscillation of a n-skin relative to the core

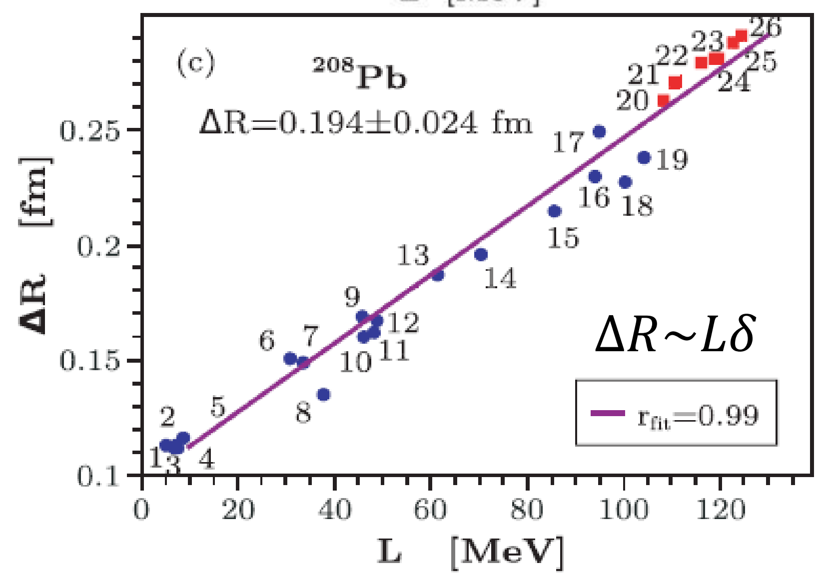


PDR and Symmetry Energy

A. Carbone et al., PRC 81, 041301 (2010)







- ✓ Recent developments
  - Dr. Victor Voronov in the first day
  - Dr. Yulia Parfenova yesterday

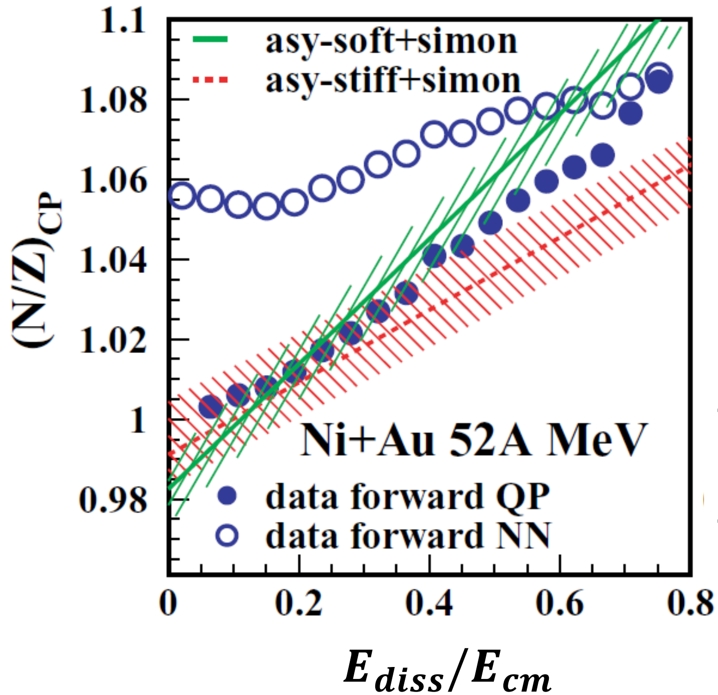
Charge Equilibration

- Charge equilibration
  - In fusion, dipole oscillation is important.
  - In deep inelastic coll., dipole oscillation is overdamped: Diffusion of charges

$$D(t) = D(0)\exp\left(-t/\tau_d\right) \qquad \left(\tau_d \leftrightarrow E_{sym}\right)$$

  - Degree of equilibration governed by contact time and symmetry energy

- Observable: N/Z of light charged particles emitted by PLF as a function of dissipated energy: $(N/Z)_{CP}$ vs. $E_{diss} \equiv E_{cm} - E_{kin}(PLF + TLF)$



E. Galichet et al., PRC 79, 064615 (2009)

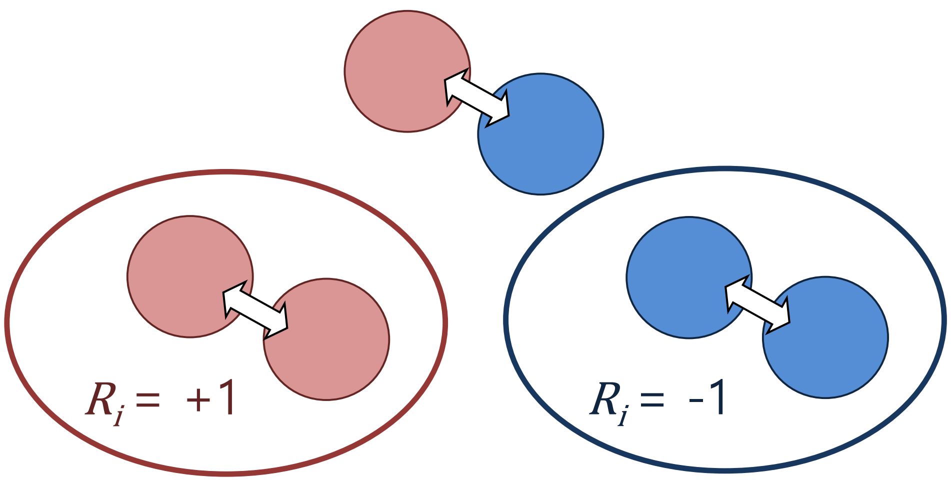
Isospin Transport/Diffusion

F. Rami et al., FOPI, PRL 84, 1120 (2000)

B. Hong et al., FOPI, PRC 66, 034901 (2002)

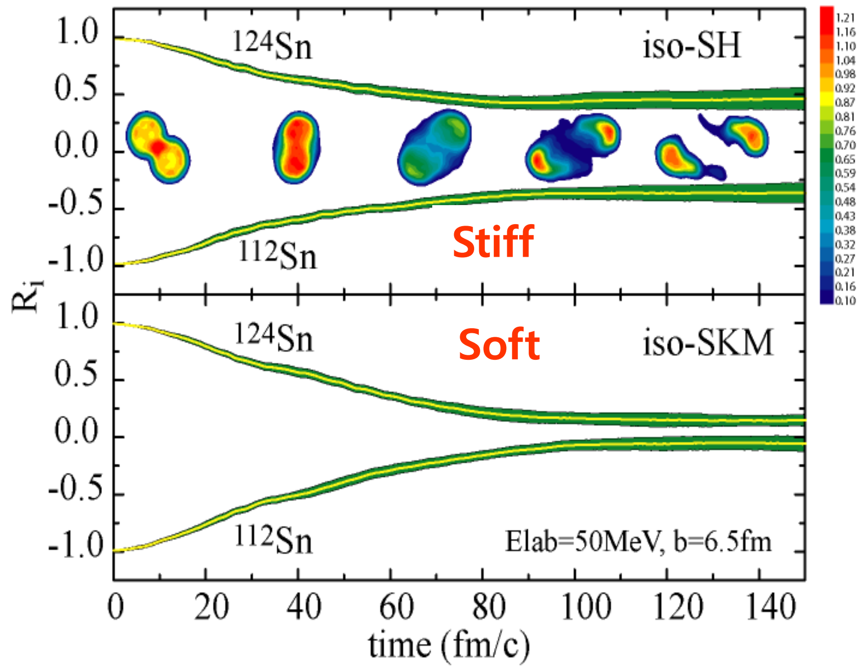
$$R_i = 2\frac{N^{AB} - (N^{AA} + N^{BB})/2}{N^{AA} - N^{BB}}$$

R_i = 0 for complete isospin mixing



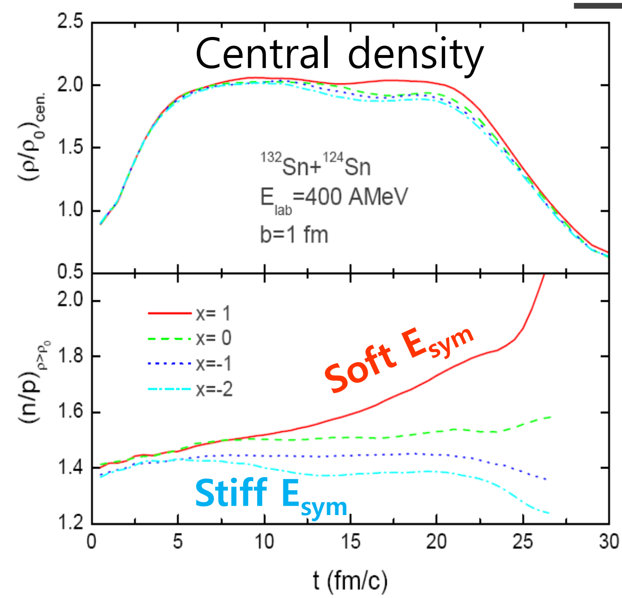
- Isospin diffusion occurs only in asymmetric collision system A+B

M.B. Tsang et al., PRL 92, 062701 (2004)



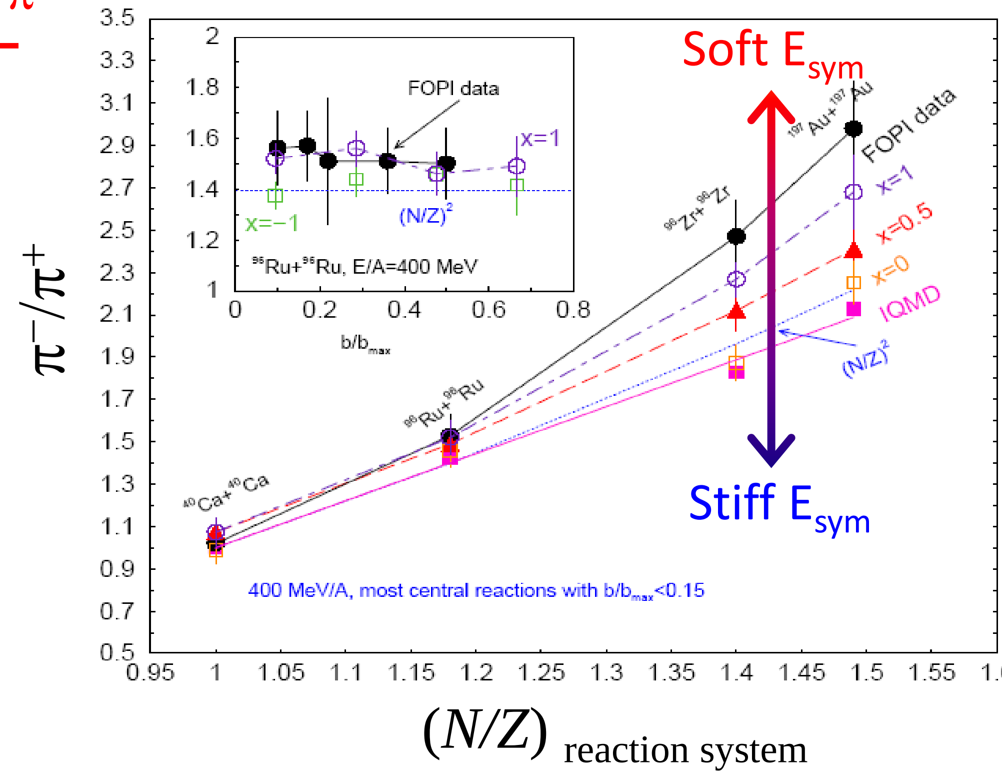
- Symmetry energy drives system towards equilibrium
- Soft E_{sym} causes large diffusion & fast equilibrium as $R_i \rightarrow 0$

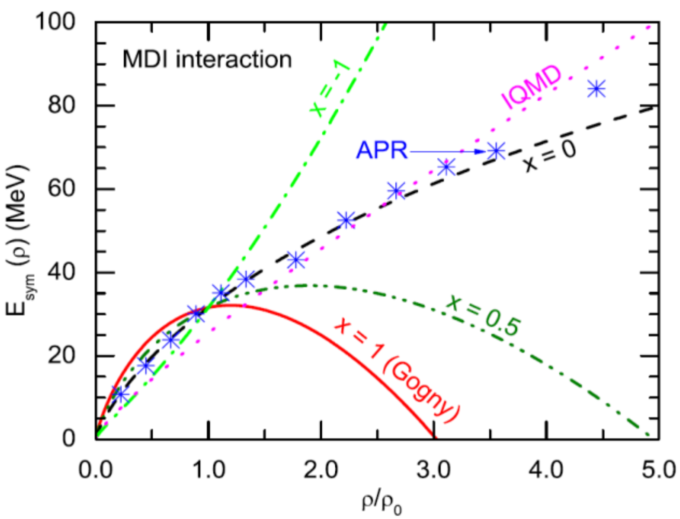
Pion Ratio



π^-/π^+

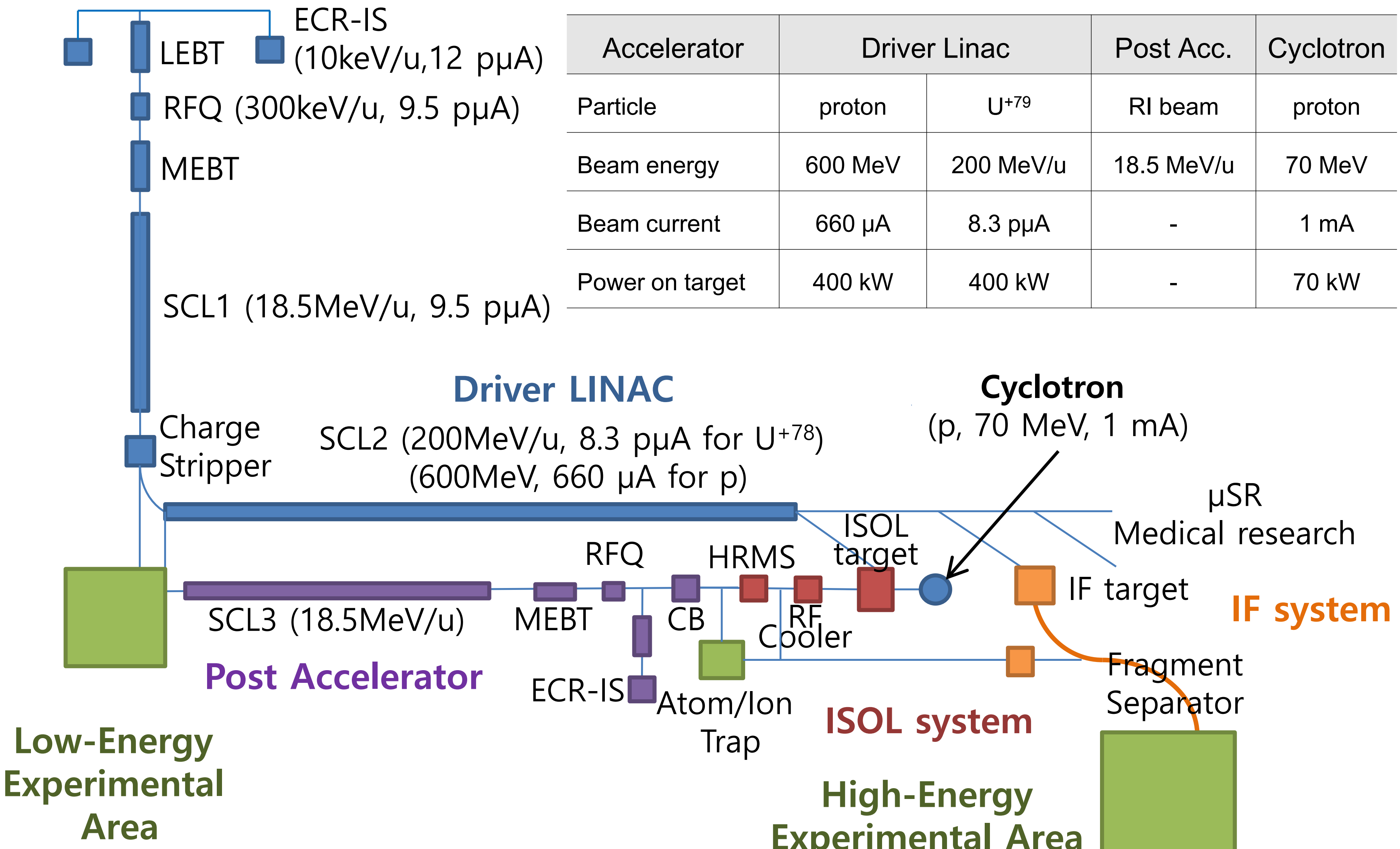
FOPI, NPA 781, 459 (2007)
Central (b/b_{max} < 0.15) at 400 AMeV



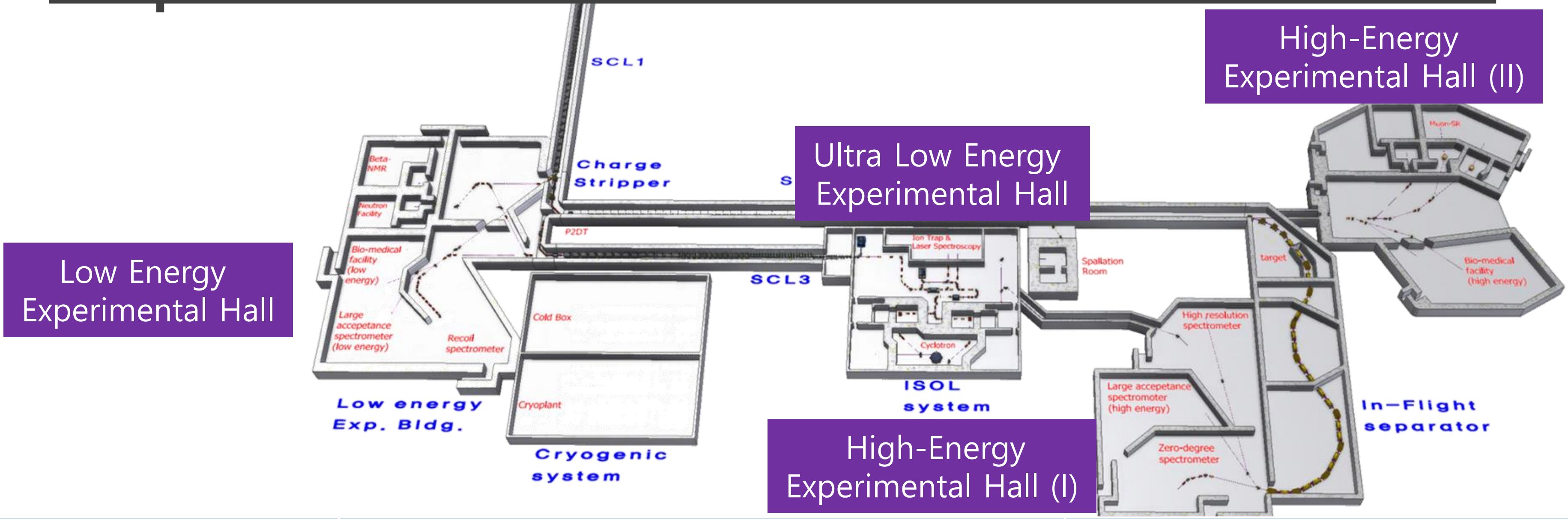


RAON

Accelerator	Driver Linac		Post Acc.	Cyclotron
Particle	proton	U^{+79}	RI beam	proton
Beam energy	600 MeV	200 MeV/u	18.5 MeV/u	70 MeV
Beam current	660 μA	8.3 pμA	-	1 mA
Power on target	400 kW	400 kW	-	70 kW

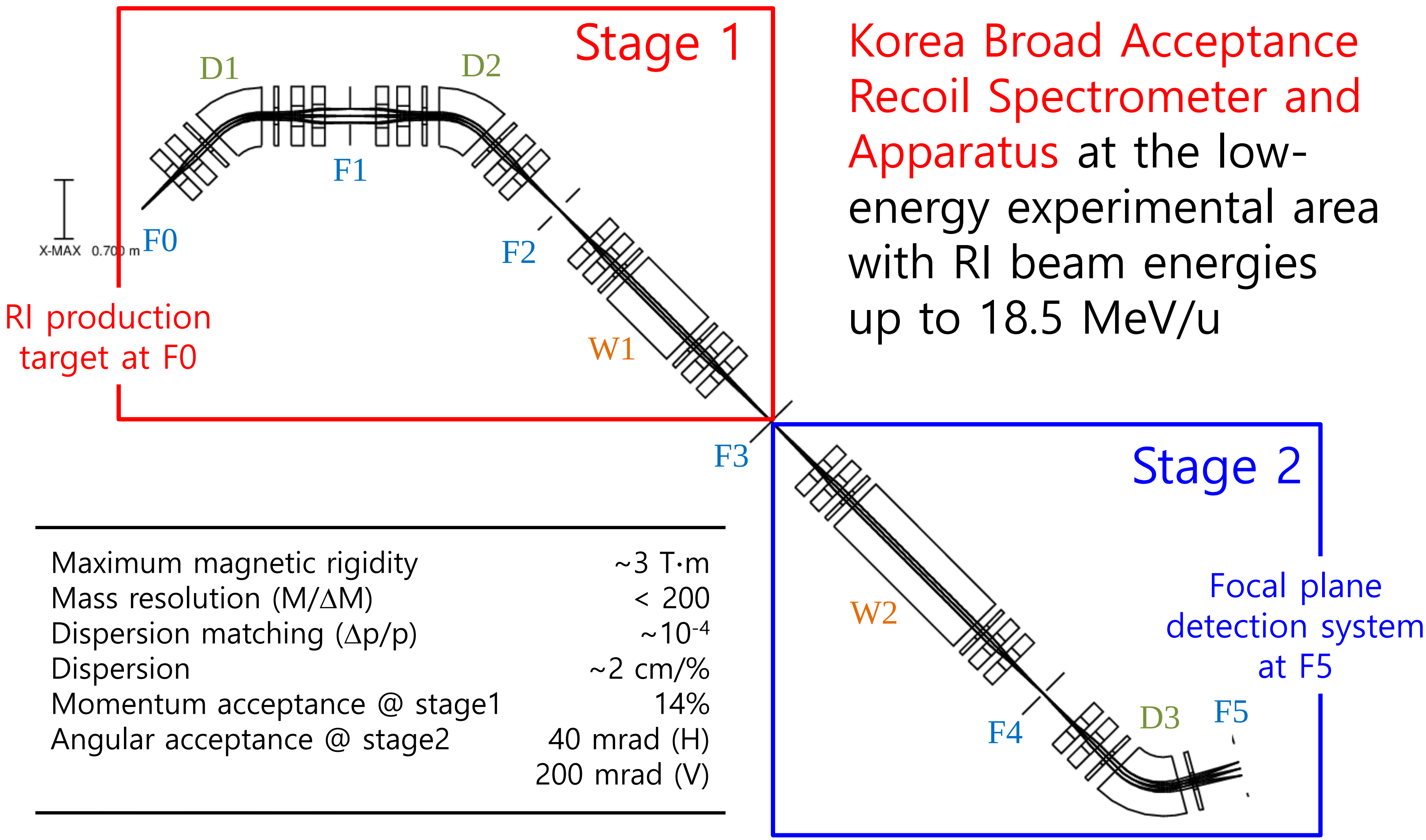


Experimental Facilities @ RAON



Experimental Hall	Experimental Setups	Relevant Science
Ultra-Low Energy	High-precision Mass Measurement System Collinear Laser Spectroscopy System	Origin of matter Properties of exotic nuclei
Low Energy	Recoil Spectrometer: **KOBRA** Large Acceptance Spectrometer: **LAMPS-L**	Origin of matter Properties of exotic nuclei
	β-NMR System, Neutron Science Facility Bio-medical Science Facility(L)	Applied science
High Energy (I)	Large Acceptance Spectrometer: **LAMPS-H** Zero Degree Spectrometer, HRS	Origin of matter Properties of exotic nuclei
High Energy (II)	μSR System, Bio-medical Science Facility(H)	Applied science

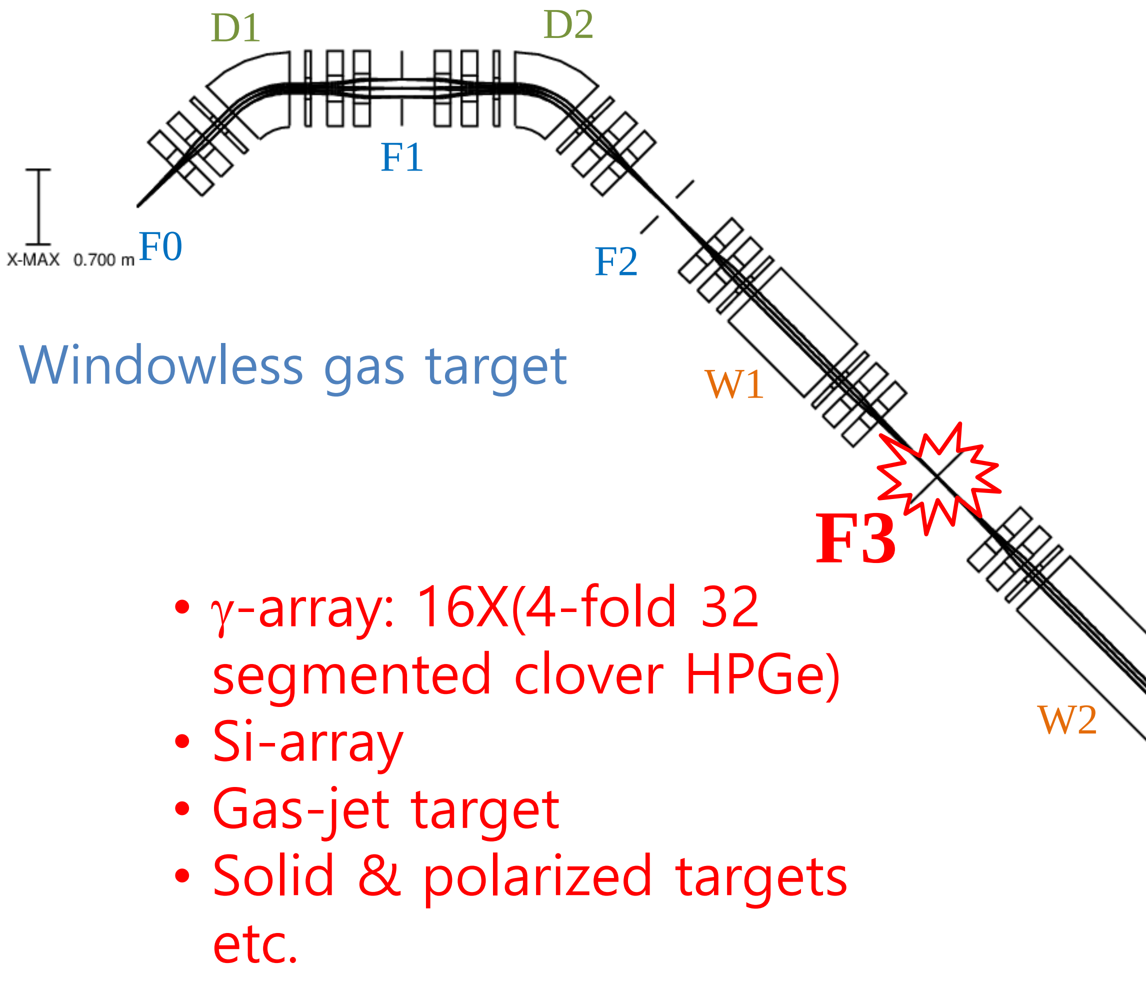
KOBRA



Korea Broad Acceptance Recoil Spectrometer and Apparatus at the low-energy experimental area with RI beam energies up to 18.5 MeV/u

Maximum magnetic rigidity	~3 T·m
Mass resolution (M/ΔM)	< 200
Dispersion matching (Δp/p)	$\sim 10^{-4}$
Dispersion	~2 cm/%
Momentum acceptance @ stage1	14%
Angular acceptance @ stage2	40 mrad (H) 200 mrad (V)

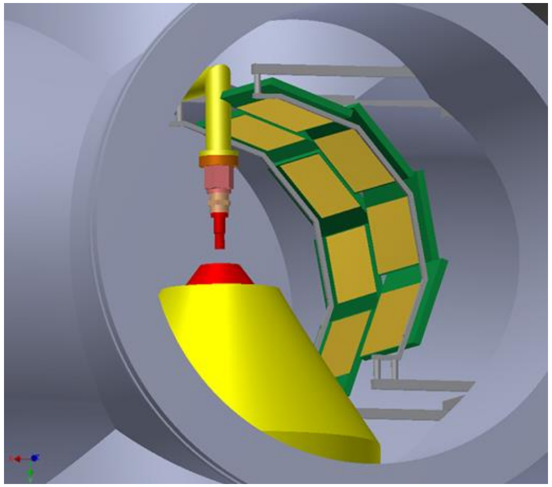
Target and Detection Systems for KOBRA



- Windowless gas target

- γ-array: 16X(4-fold 32 segmented clover HPGe)
- Si-array
- Gas-jet target
- Solid & polarized targets etc.

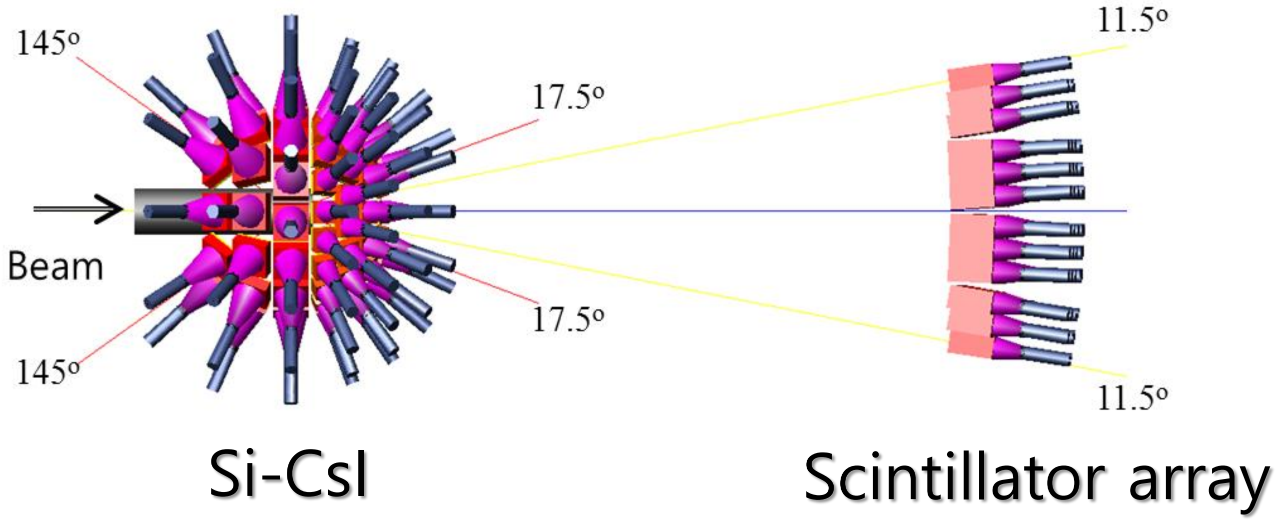
Supersonic gas-jet target



JENSA, USA

Low-Energy LAMPS (LAMPS-L)

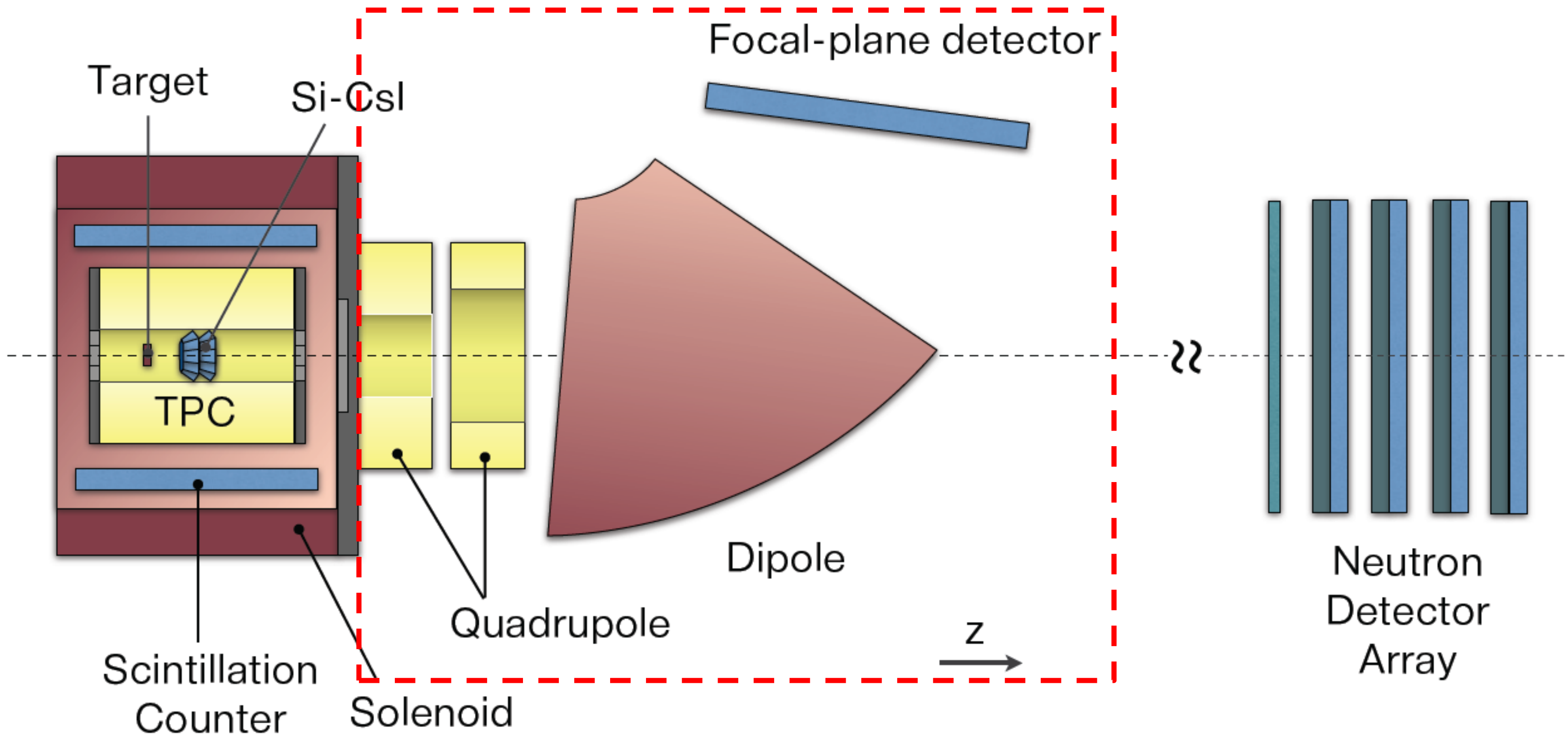
- **Si-CsI Array**
  - ✓ Charged particles & γ's
  - ✓ $\Delta E/E \sim 10^{-2}$
  - ✓ Particle ID
- **Scintillator Array**
  - ✓ Neutrons
  - ✓ Acceptance=100~300 mSr
  - ✓ $\Delta E/E \sim 5.0X10^{-2}$ via TOF



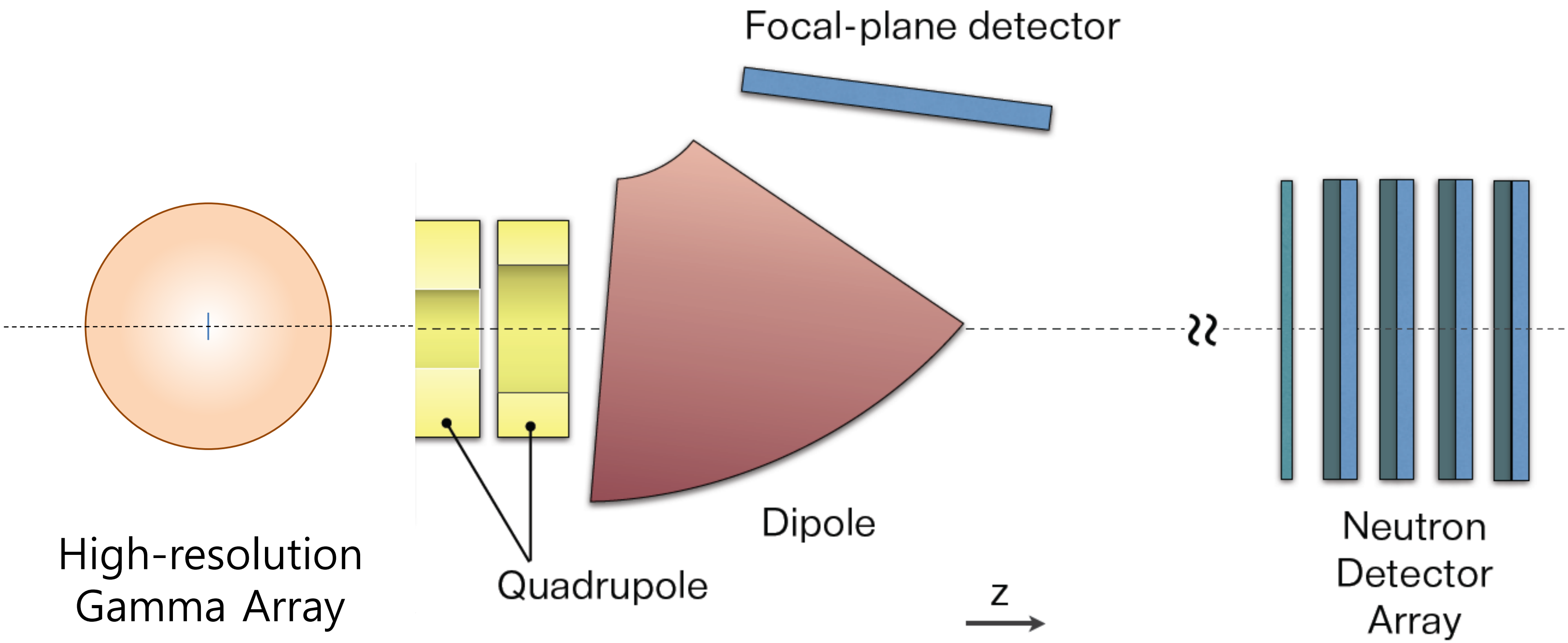
High-Energy LAMPS (LAMPS-H)

(Large-Acceptance MultiPurpose Spectrometer)

Solenoid Spectrometer ⊕ Dipole Spectrometer ⊕ Neutron Array



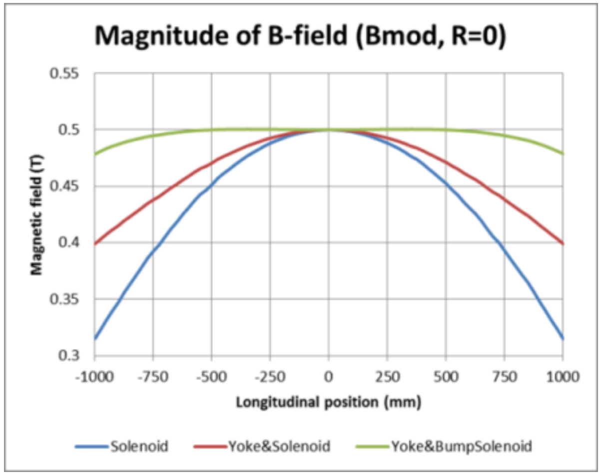
Coulomb Breakup Expts. @ LAMPS-H

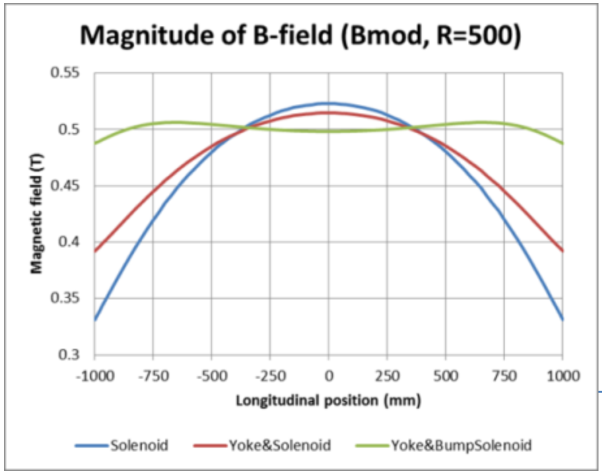


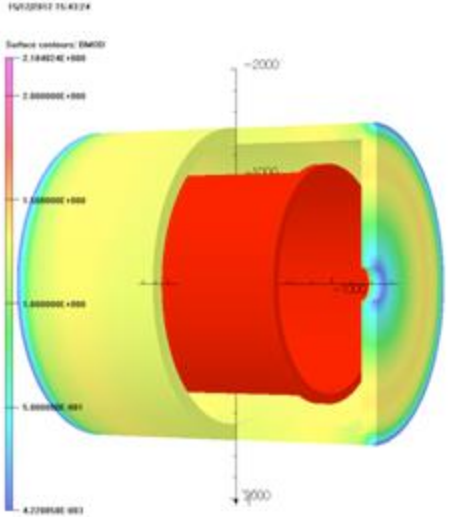
- PDR/GDR measurements
  $^{124,130,132}Sn+^{208}Pb$, $^{68,70,72}Ni+^{208}Pb$, $^{50,54,60}Ca+^{208}Pb$, etc.
- Photoabsorption measurements
  Various 1n and 2n removal cross sections for unstable nuclei
- Measurement of E^* from gamma, beam fragment, and neutrons

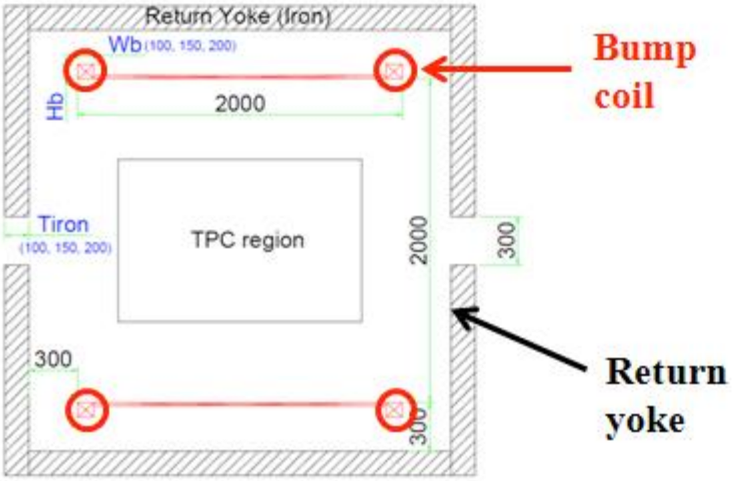
Design of Solenoid Magnet

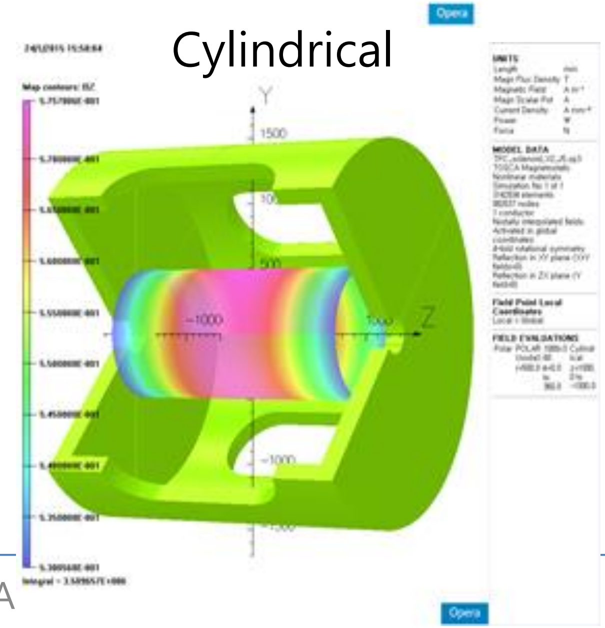
Cross section: 2.6 x 2.6 m^2
B_{op} ~ 0.5 T & B_{max} ~ 1T
$\Delta B/B$ < 2 %

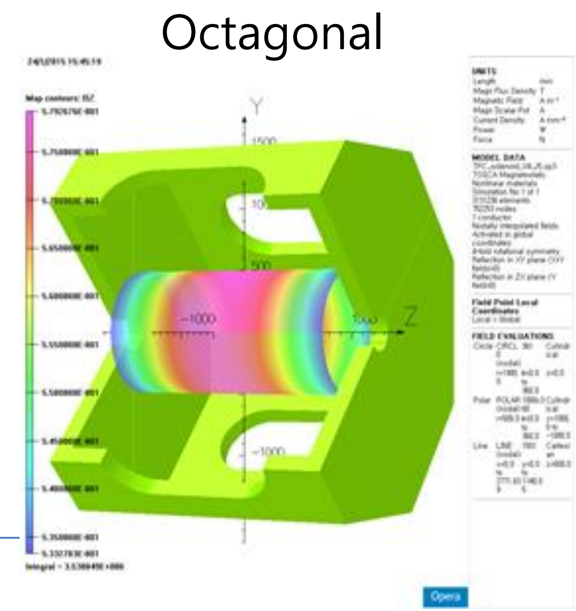






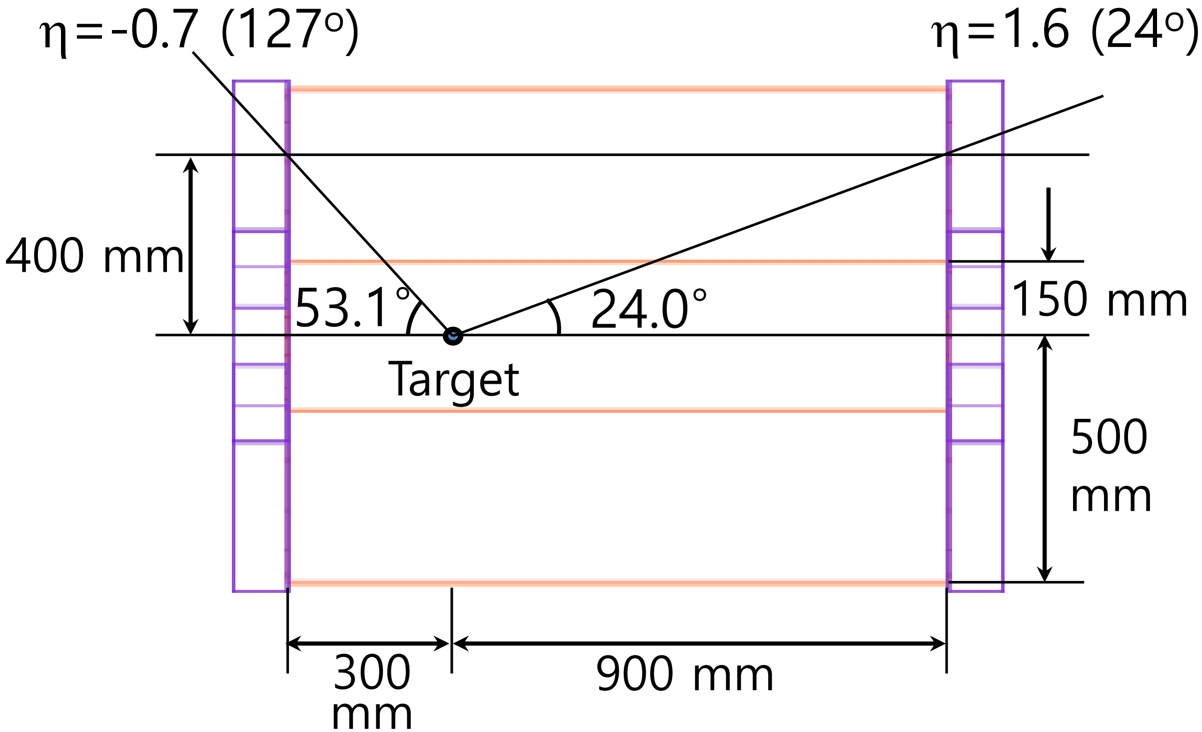




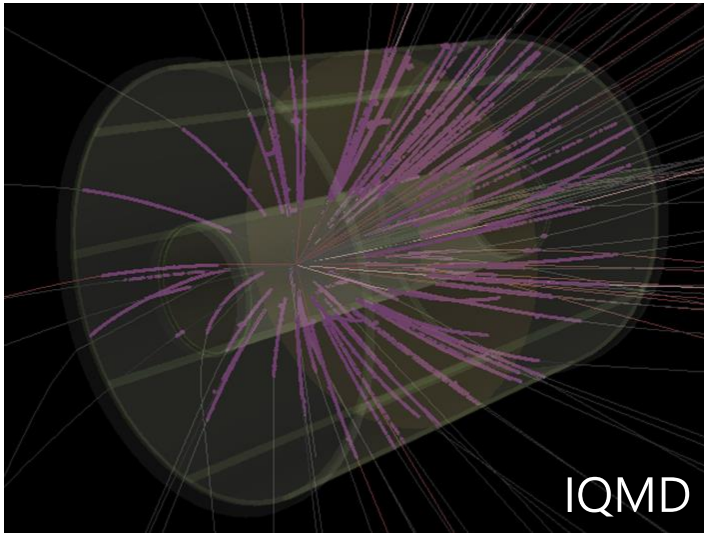


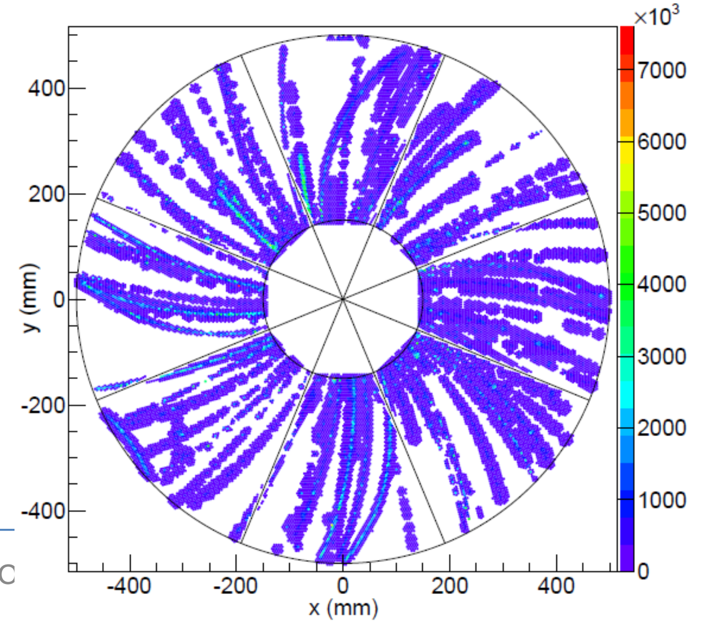
A

Time Projection Chamber



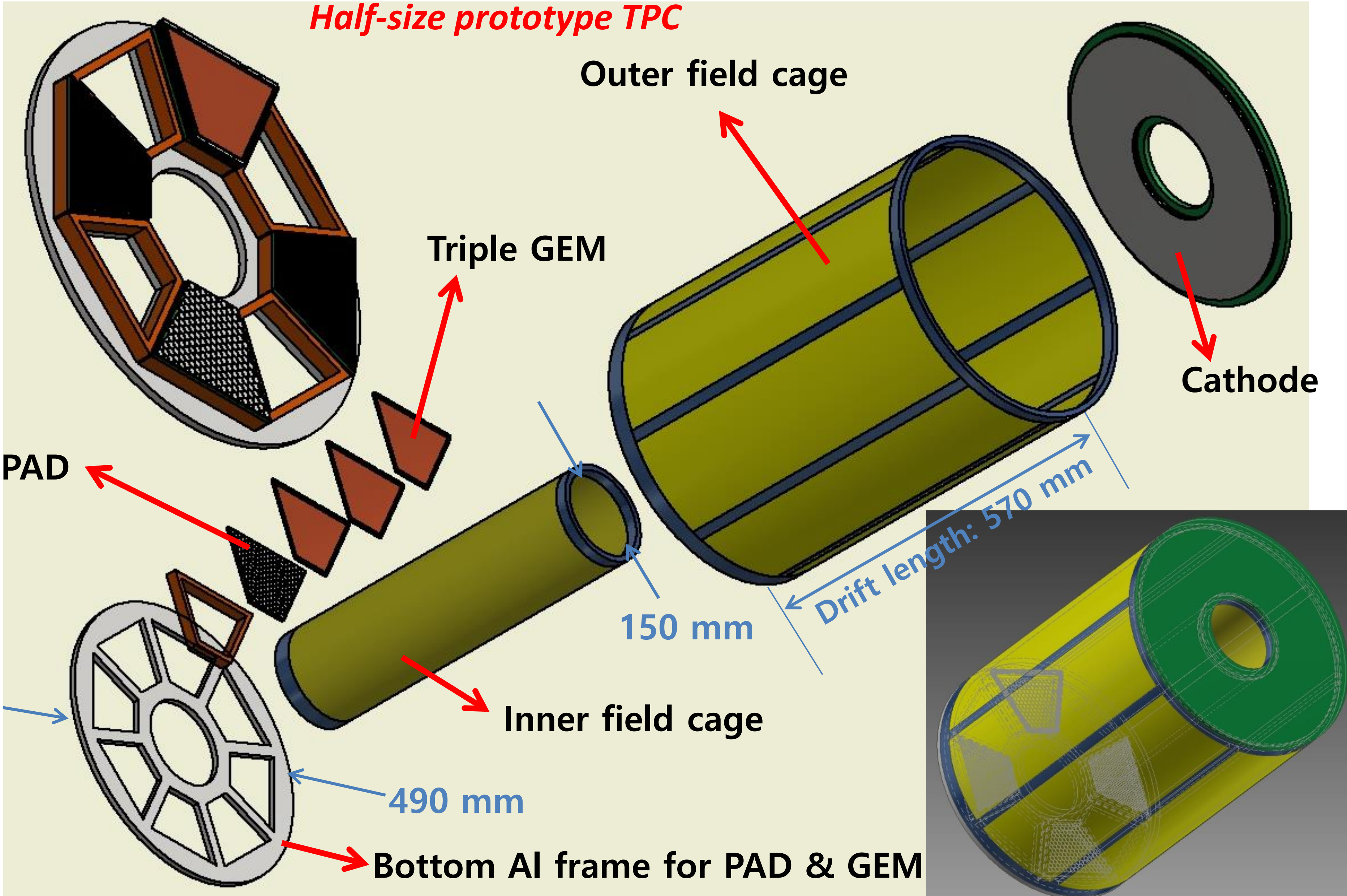
Central Au+Au at 250 AMeV





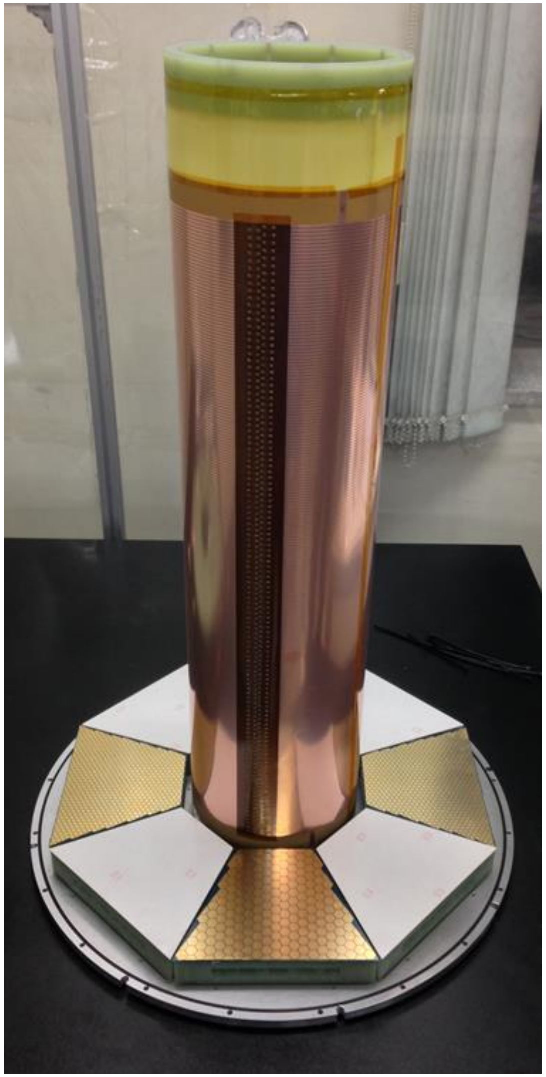
- Simulation of triple GEM by GARFIELD++
  - Gas mixture: Ar 90%+CO_2 10%
  - Voltage for each foil~450 V
  - <Gain>~$1.4X10^6$
  - <Drift velocity>~50 mm/μs
  - <Dispersion> < 3 mm

Design of ½-Size Prototype TPC

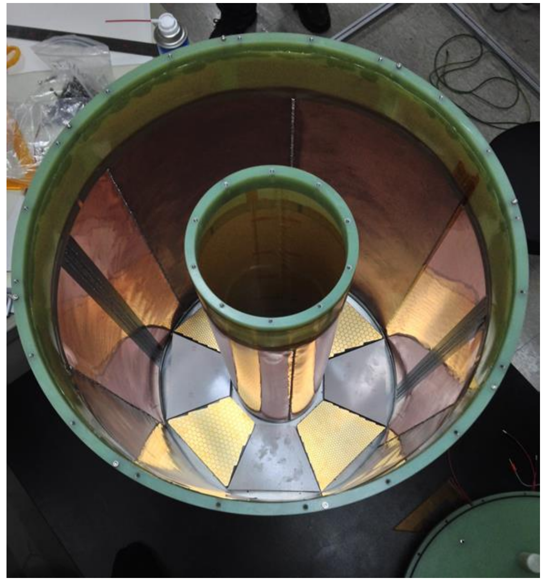


Prototype TPC-Assembly

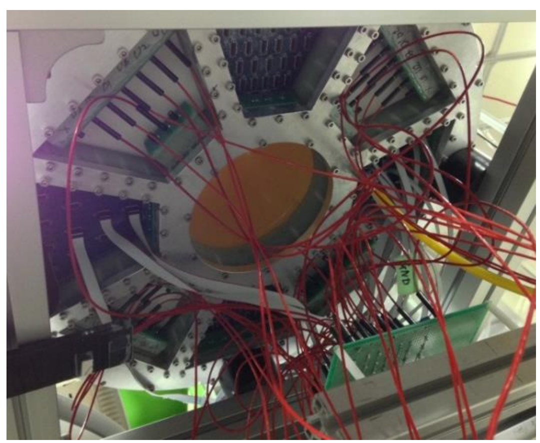
Inner Field Cage installed



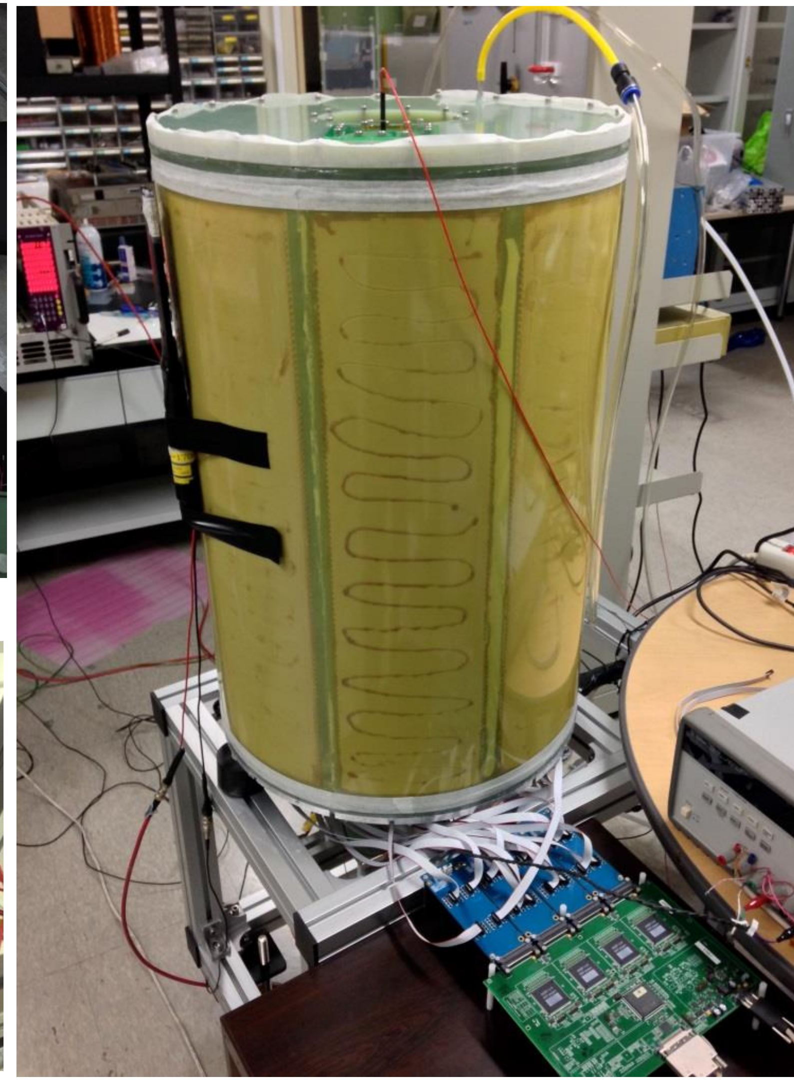
Outer Field Cage installed



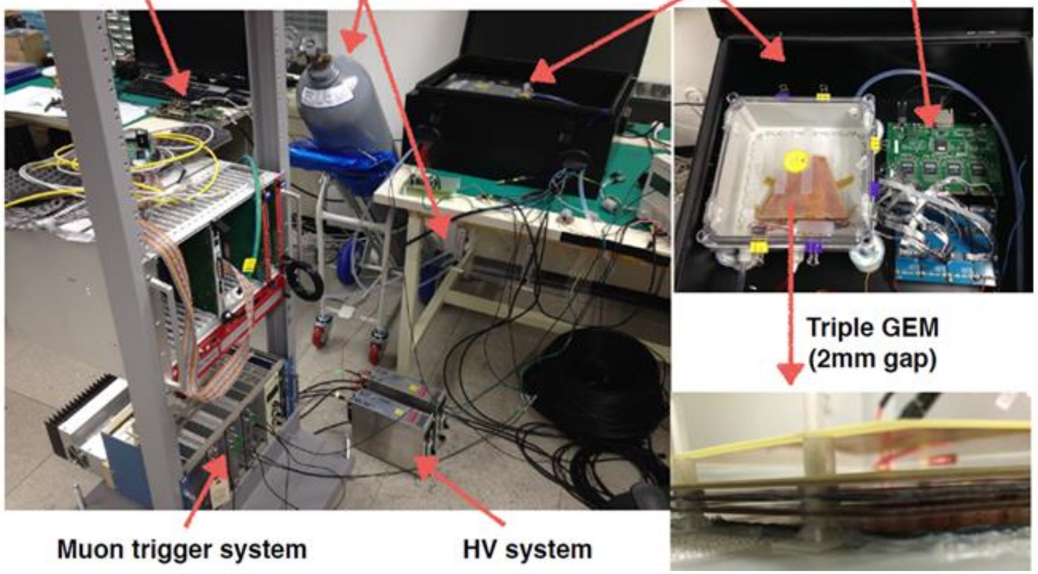
Prototype TPC: back

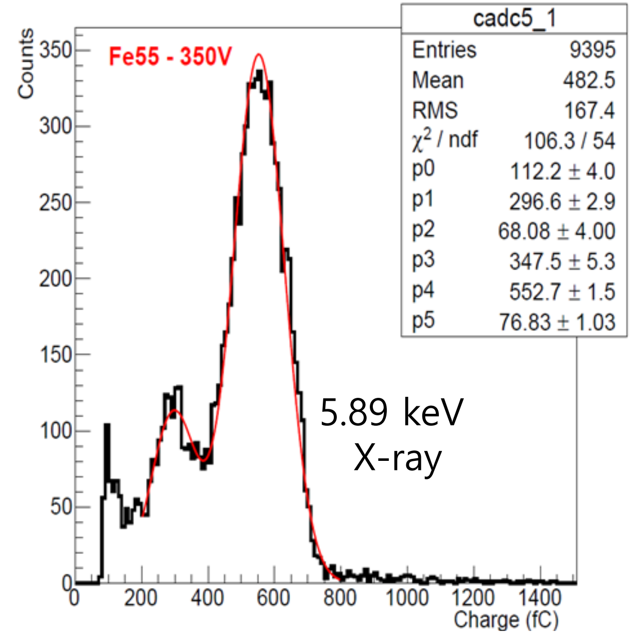


Prototype TPC assembled

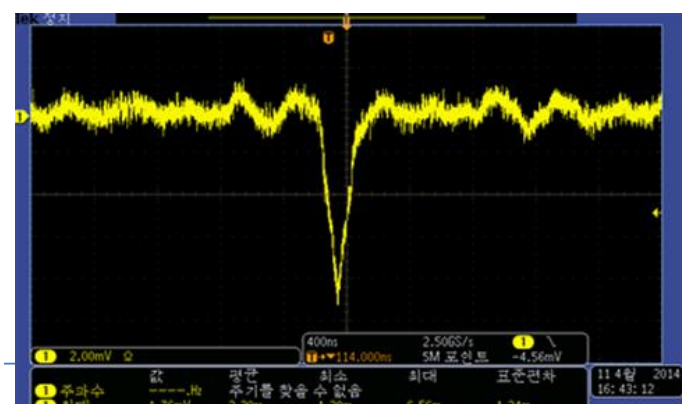


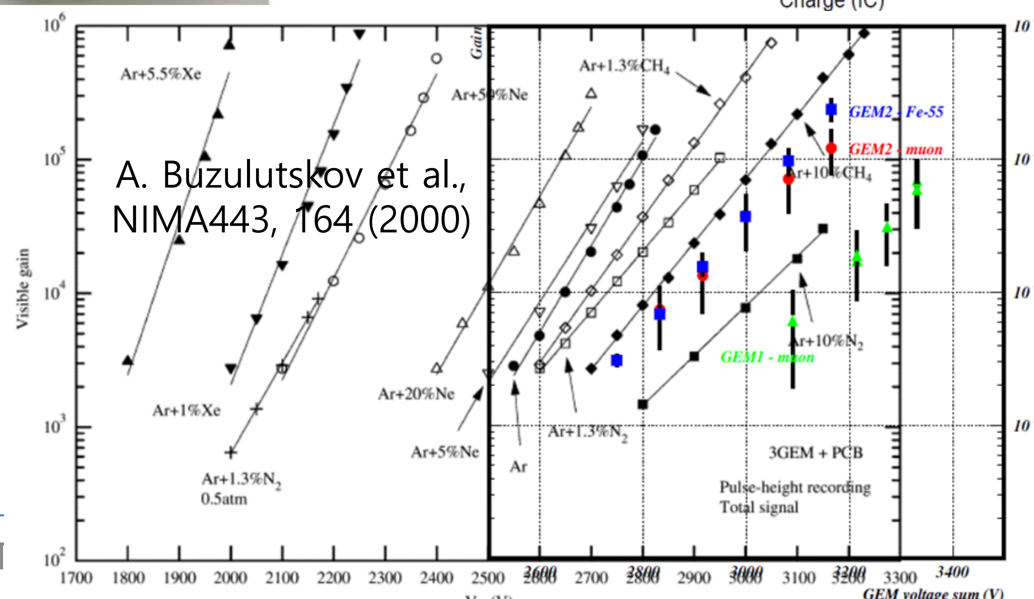
Test of Triple GEM Readout



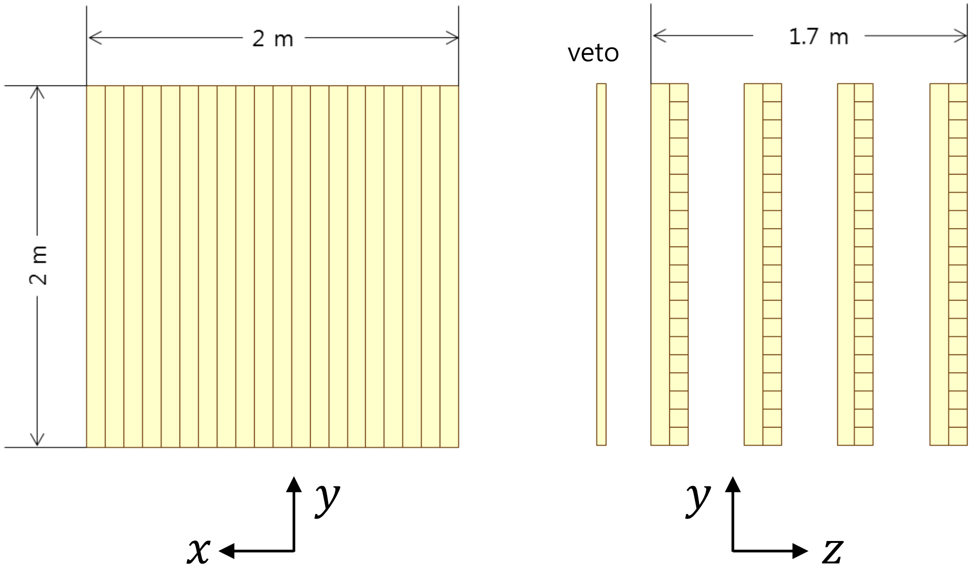


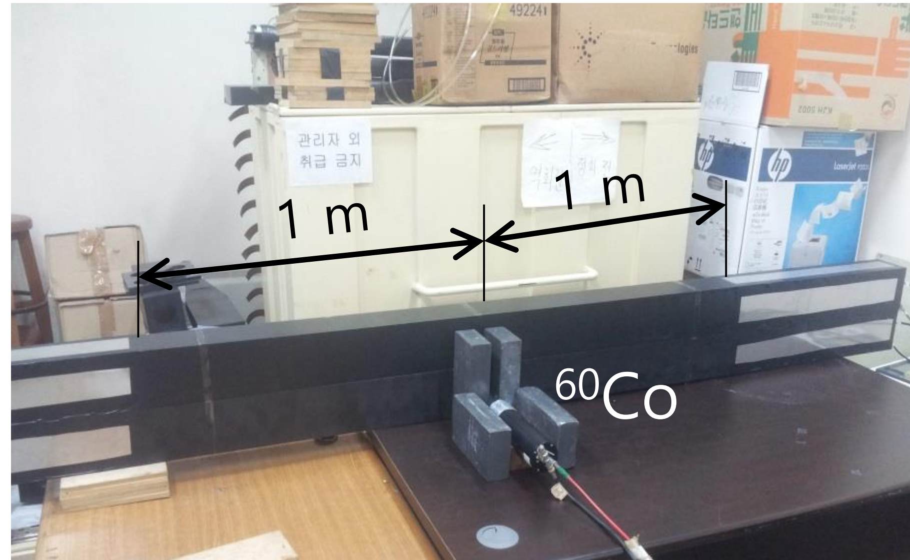
Signal from Fe-55 source





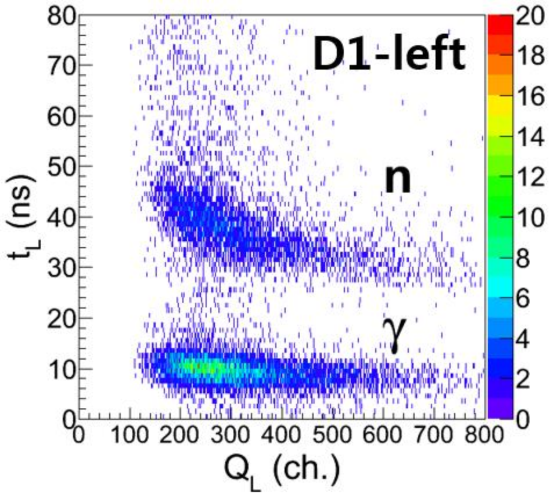
Neutron Detector Array

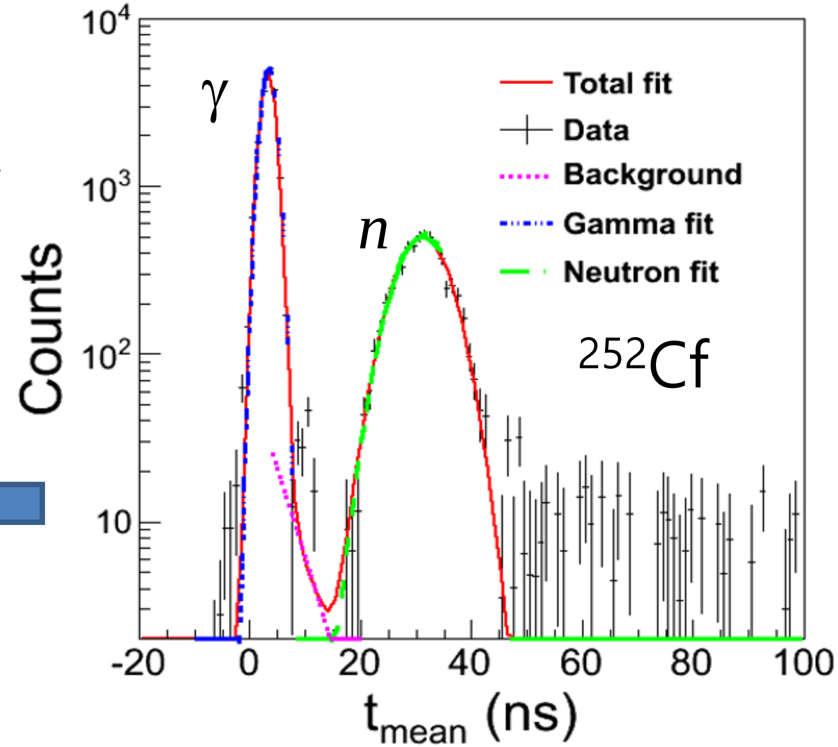


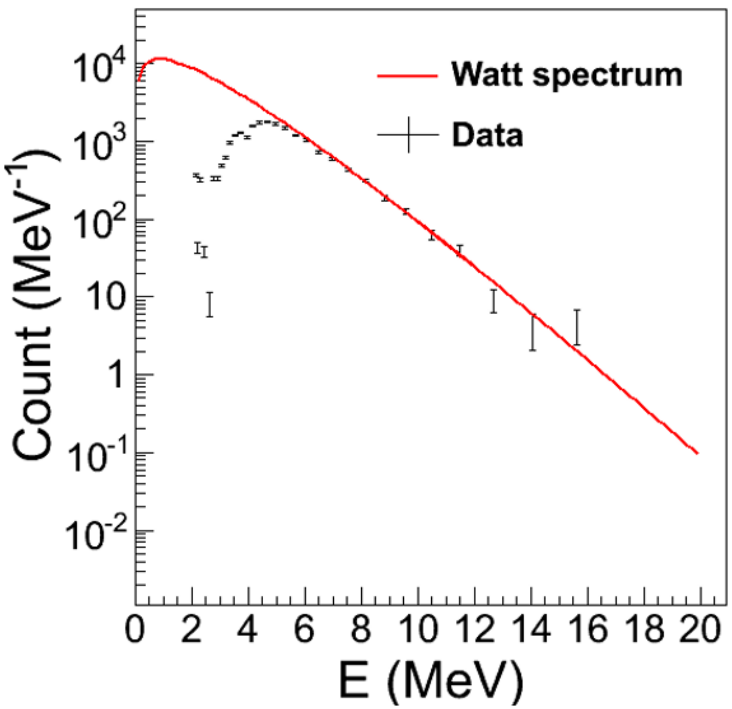


- Construction of real-size prototype detectors ($0.1 \times 0.1 \times 2.0$ m^3)
- Testing performance using ^{60}Co and ^{252}Cf sources

LAMPS Neutron Array





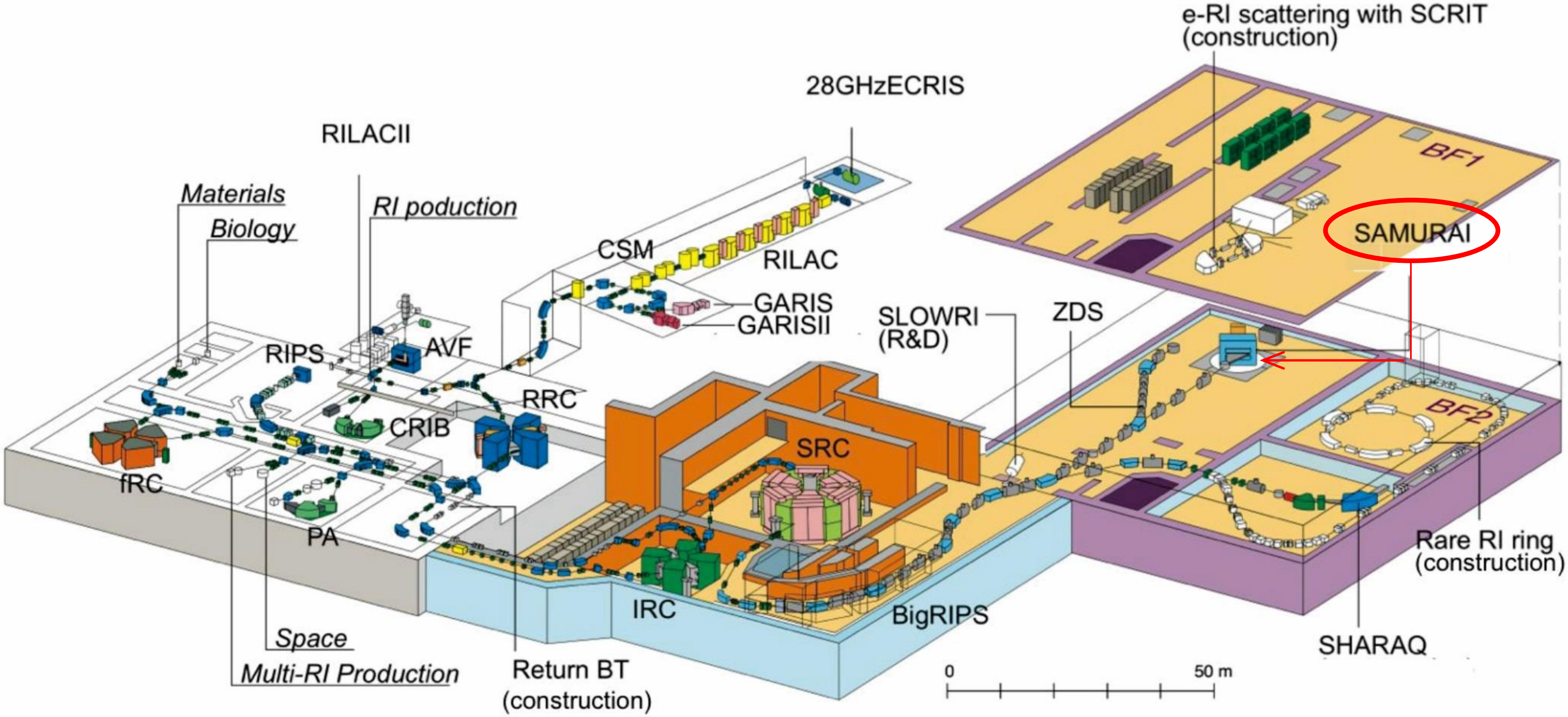


- Watt spectrum: ${}^{dN}/_{dE} \propto e^{-aE} \sinh\sqrt{bE}$
  - a=0.88 MeV^{-1} and b=2.0 MeV^{-1}
  - B. Watt, Physical Review 87, 1037 (1952)

Symmetry-Energy Research at RIBF

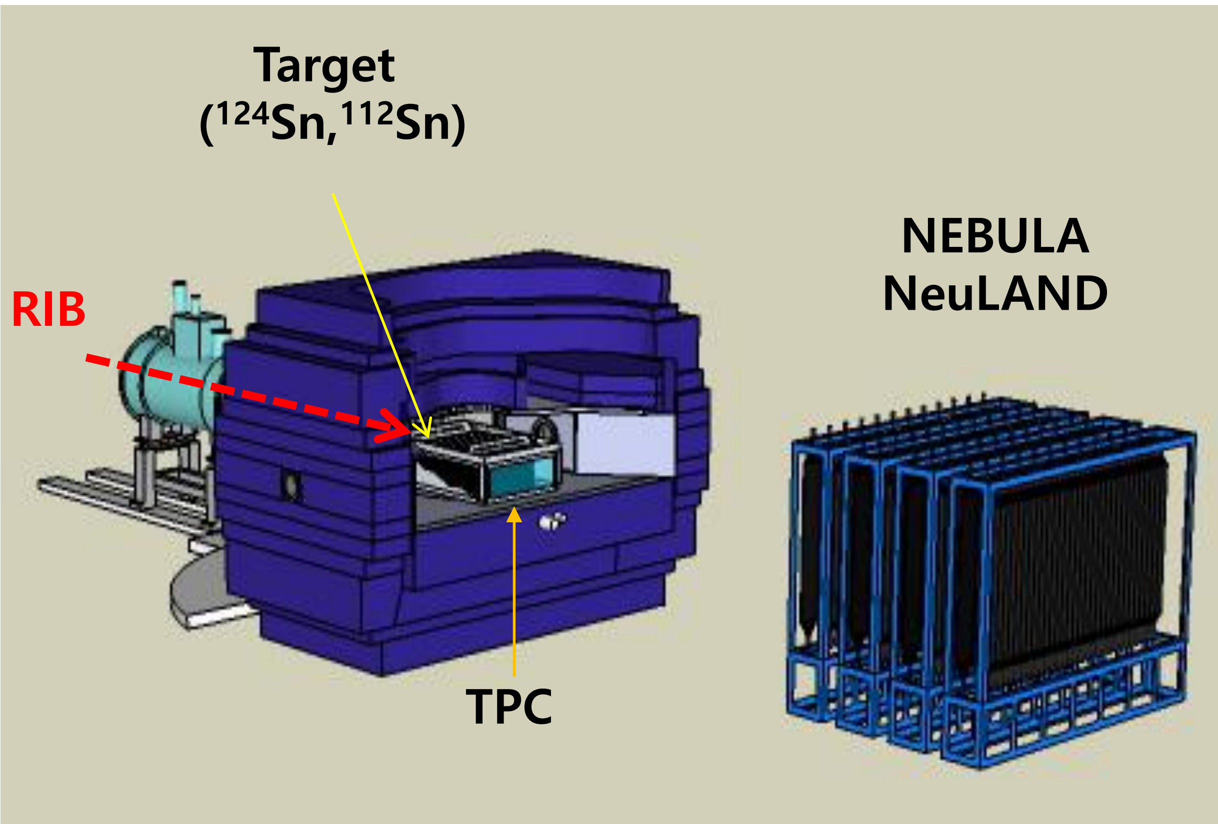
(RIBF: Rare-Isotope Beam Factory at RIKEN, Japan)

SRC: K=2500 MeV, Heavy-ion beams up to ^{238}U at 345MeV/u (Light ions up to 440MeV/u)
BigRIPS: Large acceptance fragment separator (80 mrad x 100 mrad, $\Delta P/P$~6%)



SπRIT Collaboration

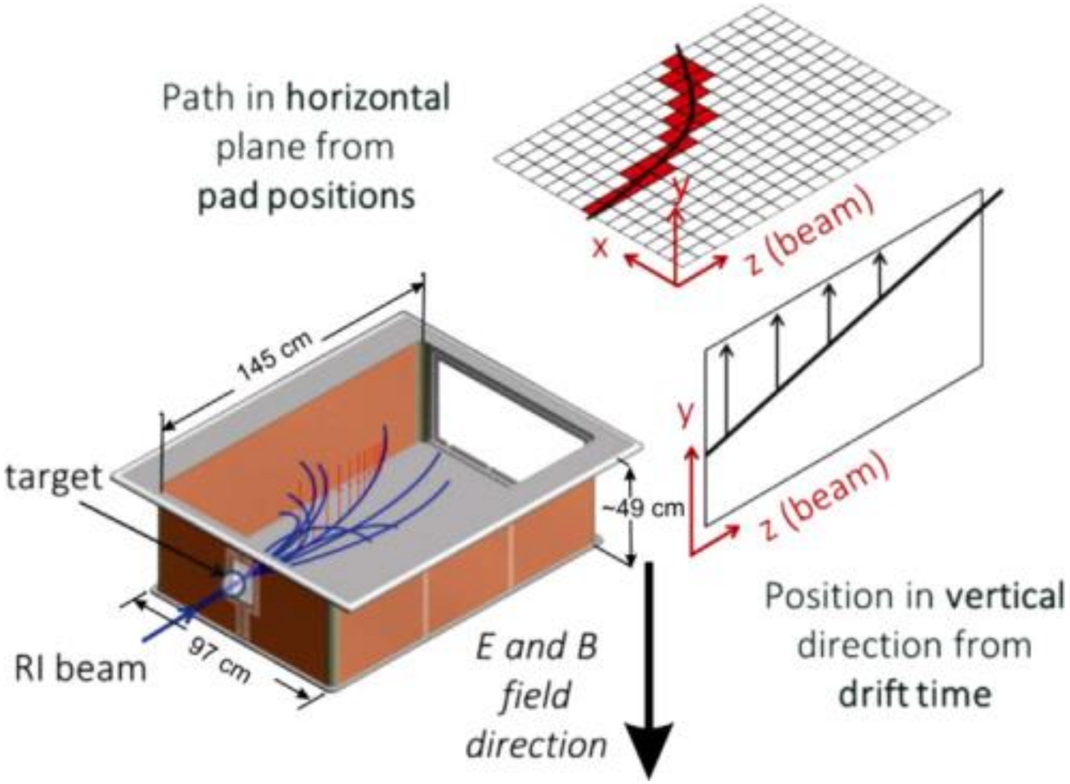
SAMURAI Pion Reconstruction and Ion-Tracker



MSU
TAMU
RIKEN
Kyoto Univ.
Rikkyo Univ.
Liverpool/Darsbury
Korea Univ.
WMU
INFN
SINAP
Tsinghua Univ.
CEA
INP
ORNL
Tohoku Univ.
TIT
GSI

SπRIT TPC

TPC Parameters	Values
Pad-plane area	1.34 x 0.86 m^2
No. of pads	12,096 (108 x 112)
Pad size	12 x 8 mm^2
Drift distance	53 cm
Pressure	1 atm
dE/dx range	Z=1-8 with GET
Two-track resolution	2.5 cm
Multiplicity limit	200 (This may impact the absolute π eff. in large systems.)



Current Status of SπRIT

1. We are testing entire SπRIT system using cosmic rays.
2. We will be ready to measure $\pi^{\pm}$ and light fragments at 300 AMeV by spring of next year (2016).

Primary	Beam	Target	E_{beam}/A	δ_{sys}	Goal	Days
^{238}U	^{132}Sn	^{124}Sn	300	0.22	Probe maximum δ	3
	^{124}Sn	^{112}Sn	300	0.15	Probe intermediate δ	3
^{124}Xe	^{108}Sn	^{112}Sn	300	0.09	Probe minimum δ	3
	^{112}Sn	^{124}Sn	300	0.15	Probe intermediate δ	3

Summary

1. RAON
   - First large-scale RIB facility for nuclear physics in Korea
2. KOBRA
   - To cover nuclear structure and nuclear astrophysics
   - Nuclear symmetry energy @ $\rho < \rho_0$ with LAMPS-L
3. LAMPS
   - Primary purpose is to measure the nuclear symmetry energy at @ $\rho > \rho_0$
   - Useful also for various photoabsorption processes
4. SπRIT Collaboration at RIBF
   - Plan to take the first physics data in early 2016