3rd Japan-Korea PHENIX Collaboration Meeting
RIKEN, Japan, 27-28 November 2014

Introduction to RAON & Detector Systems for Nuclear Physics

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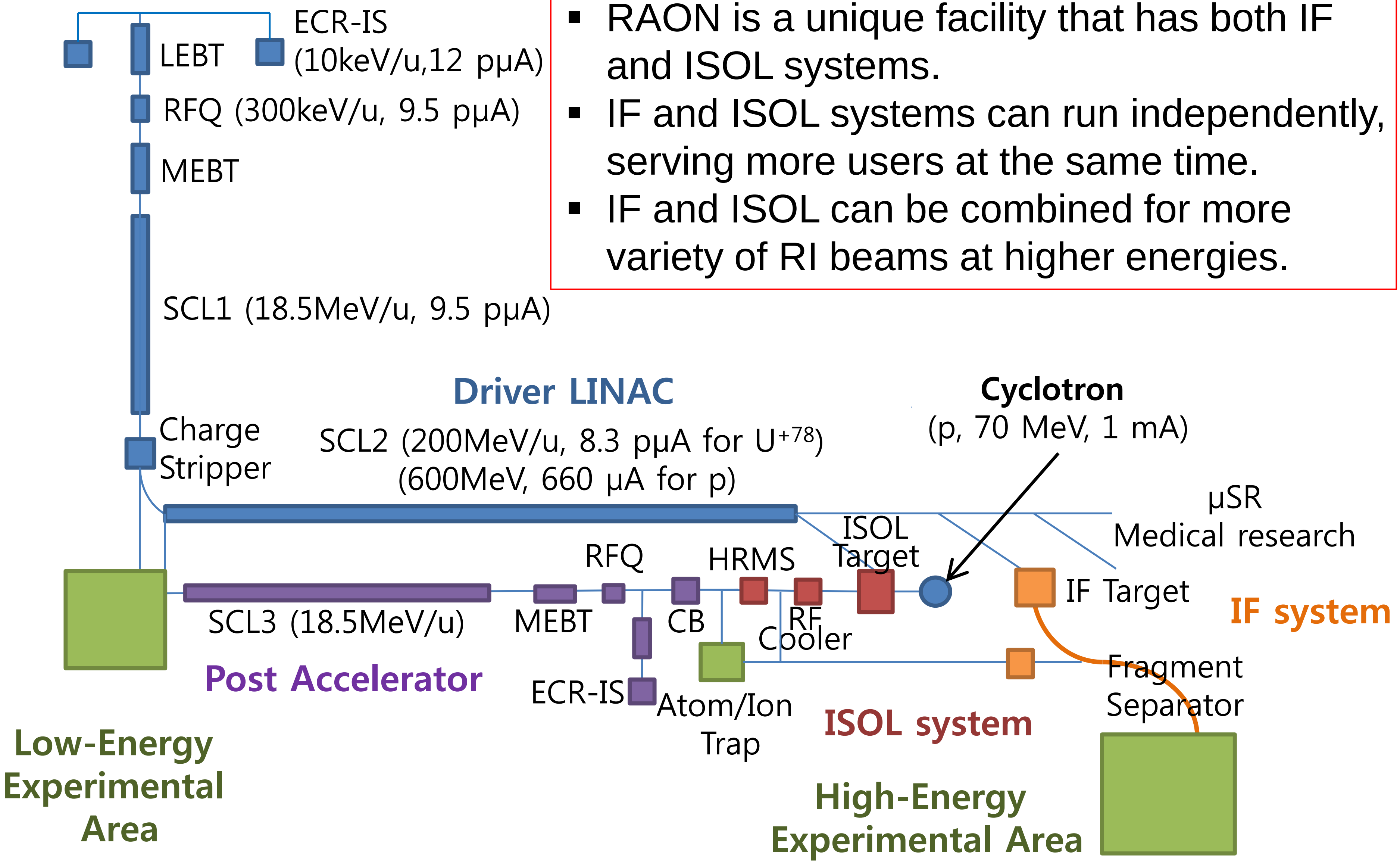
Outline

- **Plan for RAON and LAMPS in Korea**
- **Observables**
- **Status of R&D**
- **Summary**

RAON

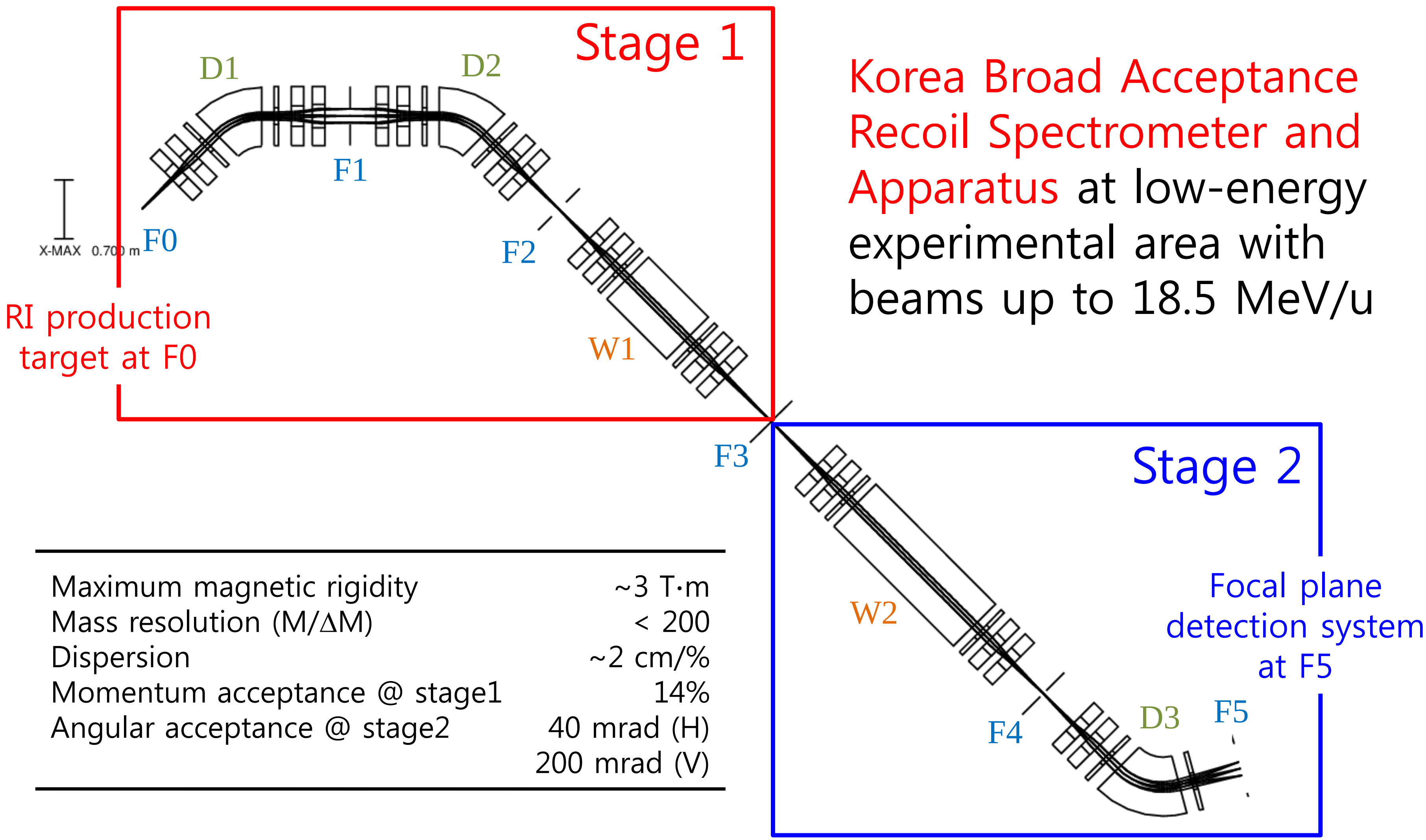
- RAON is a unique facility that has both IF and ISOL systems.
- IF and ISOL systems can run independently, serving more users at the same time.
- IF and ISOL can be combined for more variety of RI beams at higher energies.



Beam Parameters of RAON

	Driver Linac				Post Acc.	Cyclotron
Particle	H^{+}	O^{+8}	Xe^{+54}	U^{+79}	RI beam	proton
Beam energy (MeV/u)	600	320	251	200	18.5	70
Beam current (pμA)	660	78	11	8.3	-	1000
Power on target (kW)	>400	400	400	400	-	70

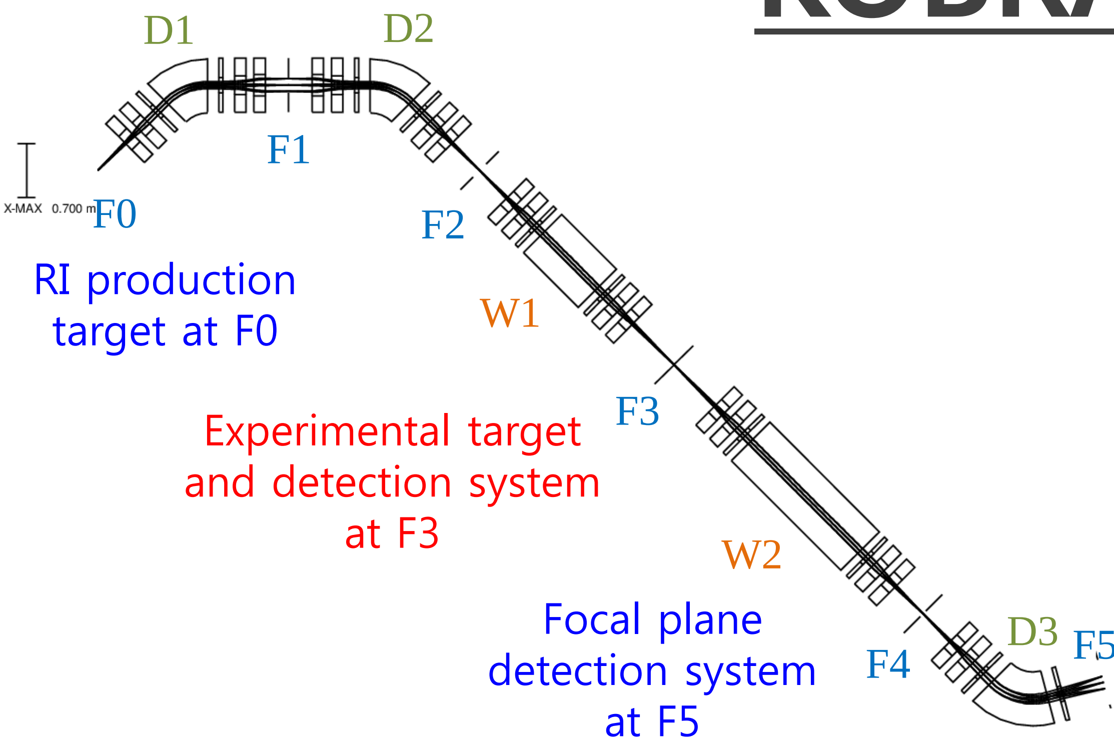
KOBRA

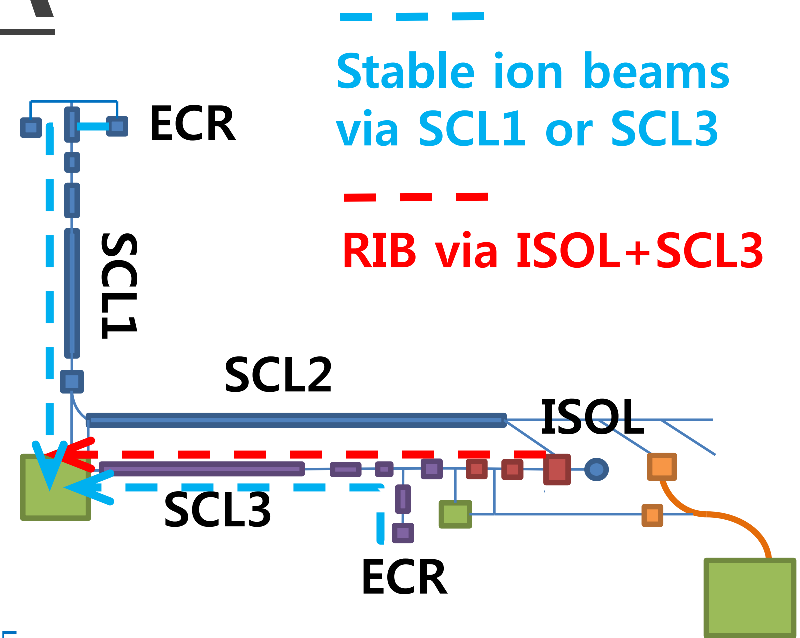


Korea Broad Acceptance Recoil Spectrometer and Apparatus at low-energy experimental area with beams up to 18.5 MeV/u

Maximum magnetic rigidity	~3 T·m
Mass resolution (M/ΔM)	< 200
Dispersion	~2 cm/%
Momentum acceptance @ stage1	14%
Angular acceptance @ stage2	40 mrad (H)
	200 mrad (V)

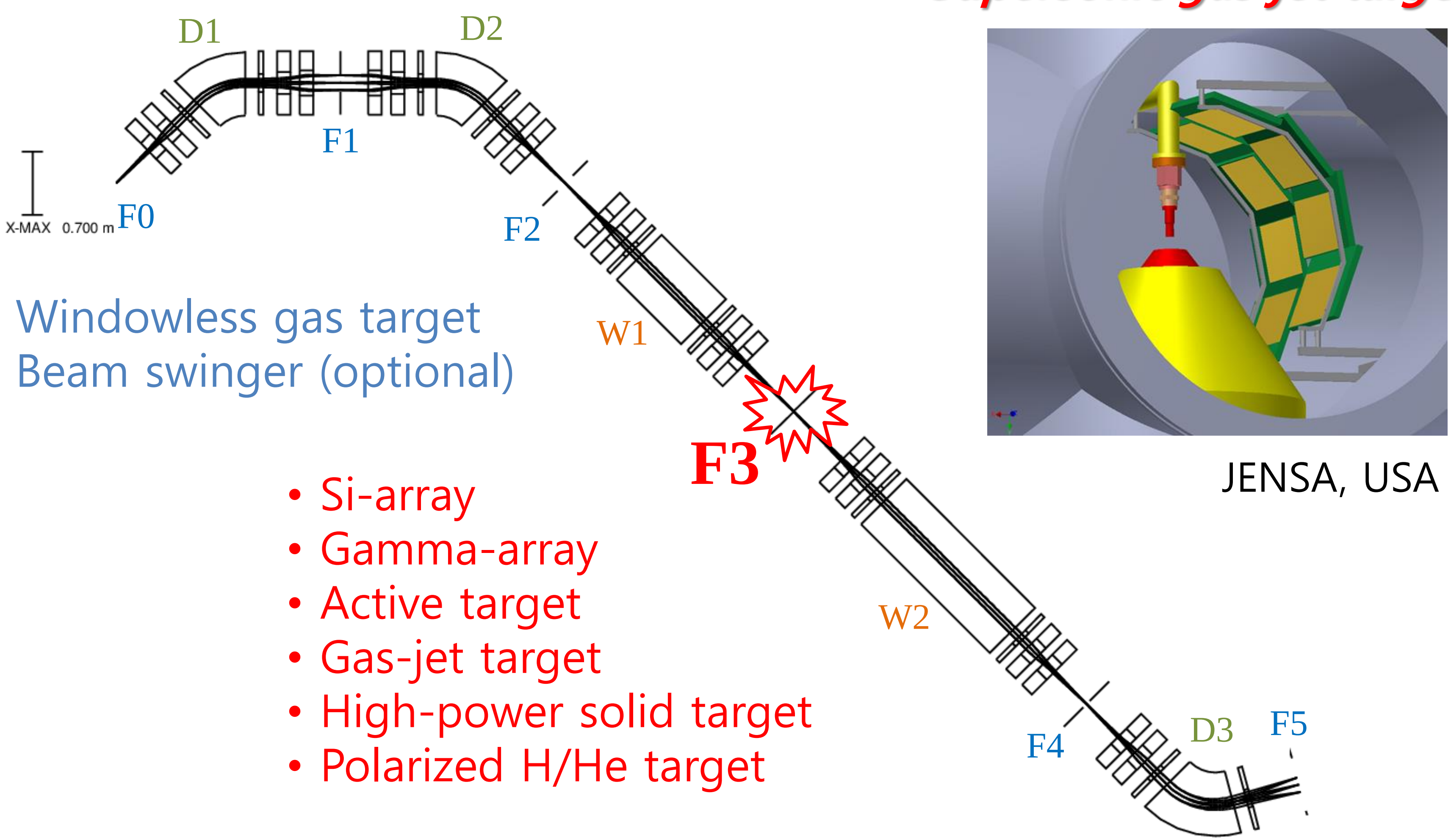
KOBRA





- Stage 1 (F0~F3): Production and separation of RIBs by in-flight method with high-intensity stable ion beams from ECRs
- Experimental target at F3 (available space of 2~3 m): In-beam γ-ray spectroscopy, Symmetry energy & charged particle spectroscopy, etc.
- Stage 2 (F3~F5): Big-bite spectrometer with Wien filter

Target and Detection Systems for KOBRA



- Windowless gas target
- Beam swinger (optional)

- Si-array
- Gamma-array
- Active target
- Gas-jet target
- High-power solid target
- Polarized H/He target

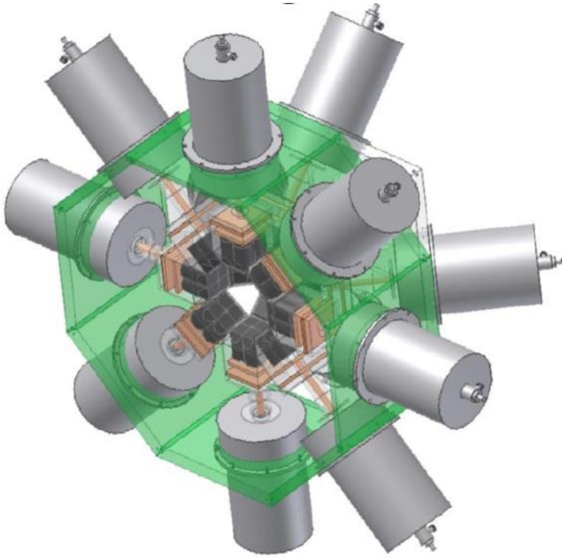
Supersonic gas-jet target

JENSA, USA

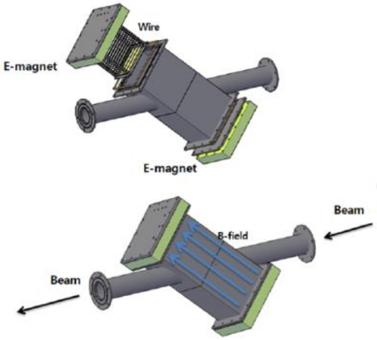
Target and Detection Systems for KOBRA

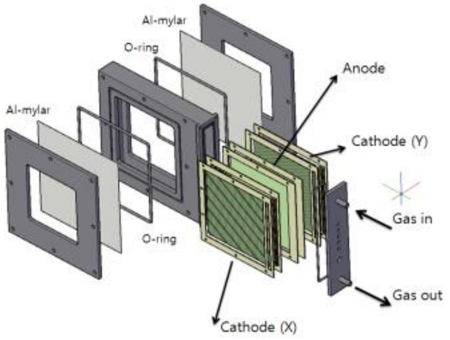
- Gamma array
  - 16X(4-fold 32 segmented Clover HPGe)
  - First half of full array: ~2018
  - Second half of full array: after 2019

Number of clovers	16 for full array
Distance from target to detector surface	107.5 mm
Angle coverage	85% for 4π
Digital electronics	TIGRESS or GRETINA

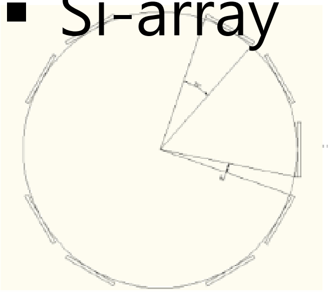


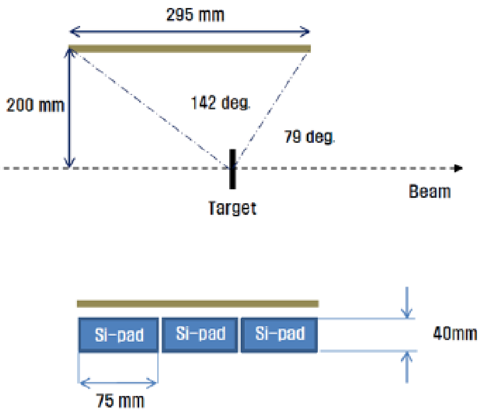
- Beam tracking detectors





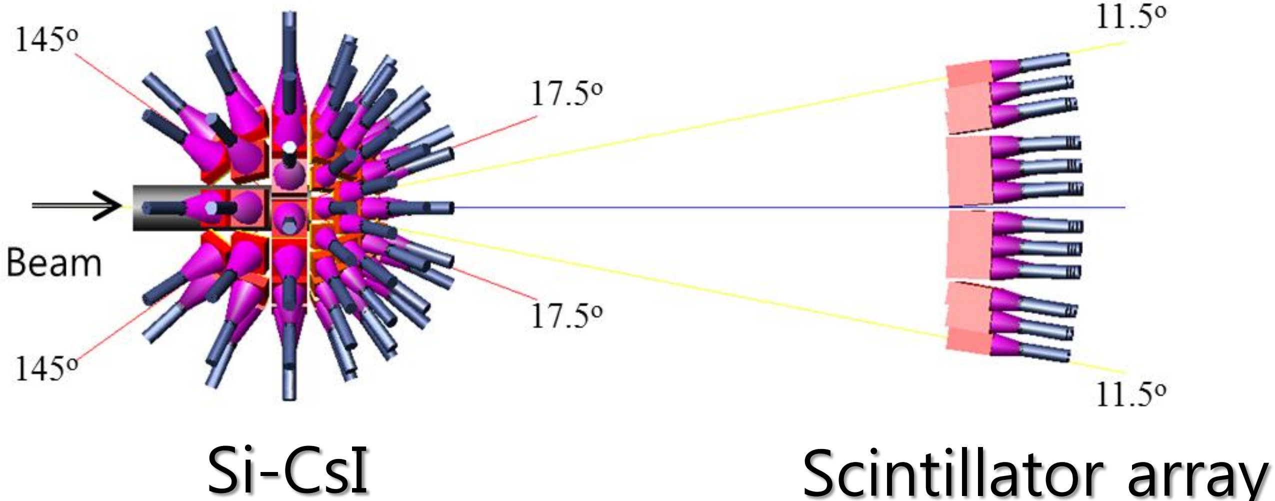
- Si-array





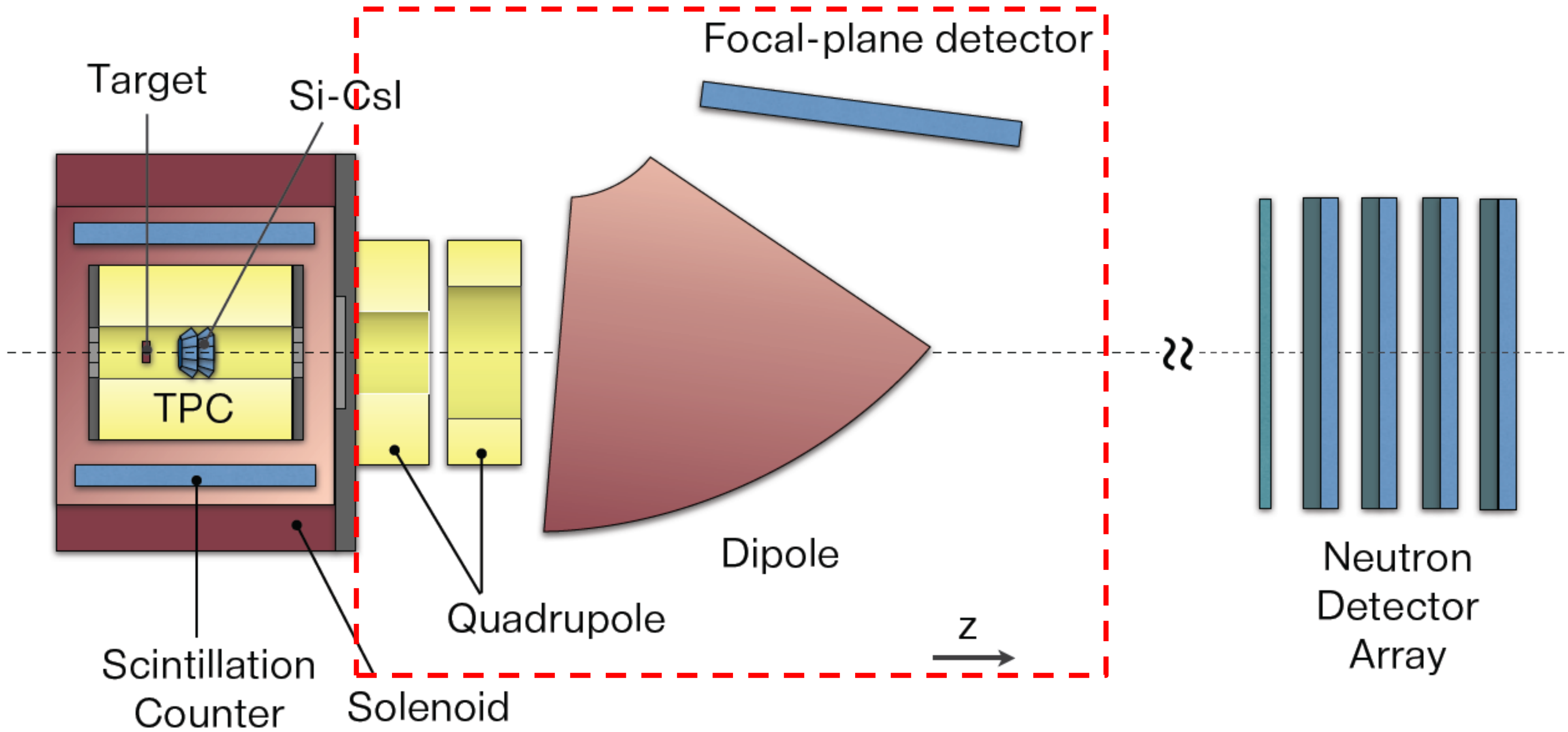
Low-Energy LAMPS (LAMPS-L)

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



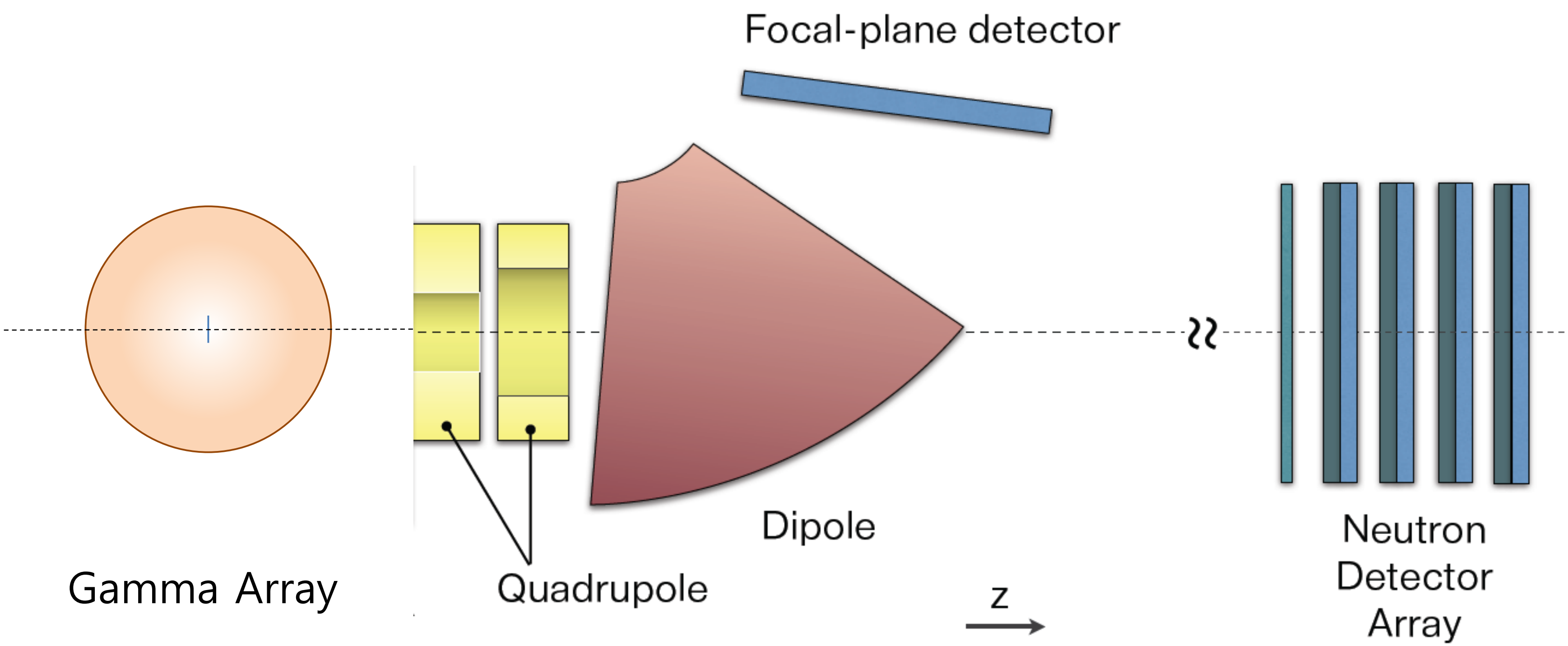
High-Energy LAMPS (LAMPS-H)

- Solenoid Spectrometer + Dipole Spectrometer + Neutron Detector Array



High-Energy LAMPS (LAMPS-H)

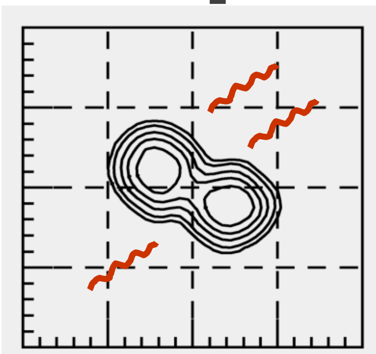
- For the various Coulomb breakup experiments



Physics Topics/Observables to be Covered by LAMPS

- Low-energy LAMPS @ KOBRA in LE Expt. area
  - Nuclear symmetry energy @ sub-saturation density
  - Fusion reaction cross section
  - Dipole emission
    - Yield & the polar angle dependence
  - Intermediate-Mass Fragments
    - Charge equilibration/Isospin mixing/Neck fragmentation
- High-energy LAMPS @ HE Expt. area
  - Nuclear symmetry energy @ supra-saturation density
  - Ratio of mirror nuclei & π^{-}/π^{+}
  - Isospin diffusion parameter
  - Collective flow
  - Dipole emission
    - For example, peak position of GDR and yield of PDR

Dipole Emission in Fusion



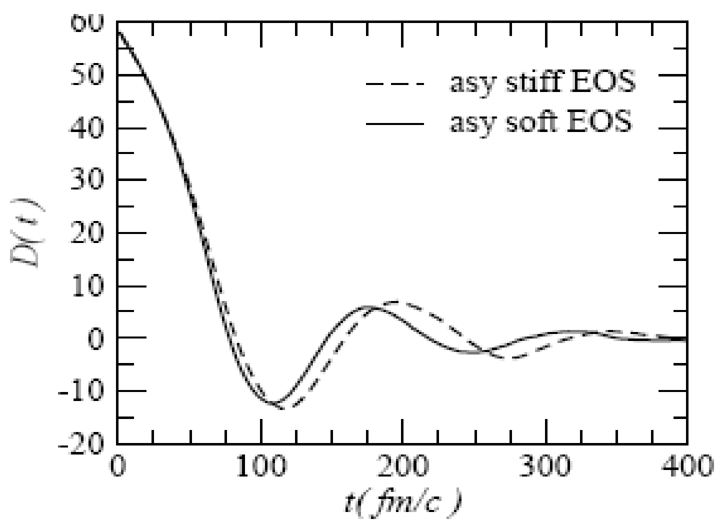
$N_1/Z_1 \neq N_2/Z_2$

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

- Collective dipole bremsstrahlung radiation during the charge 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



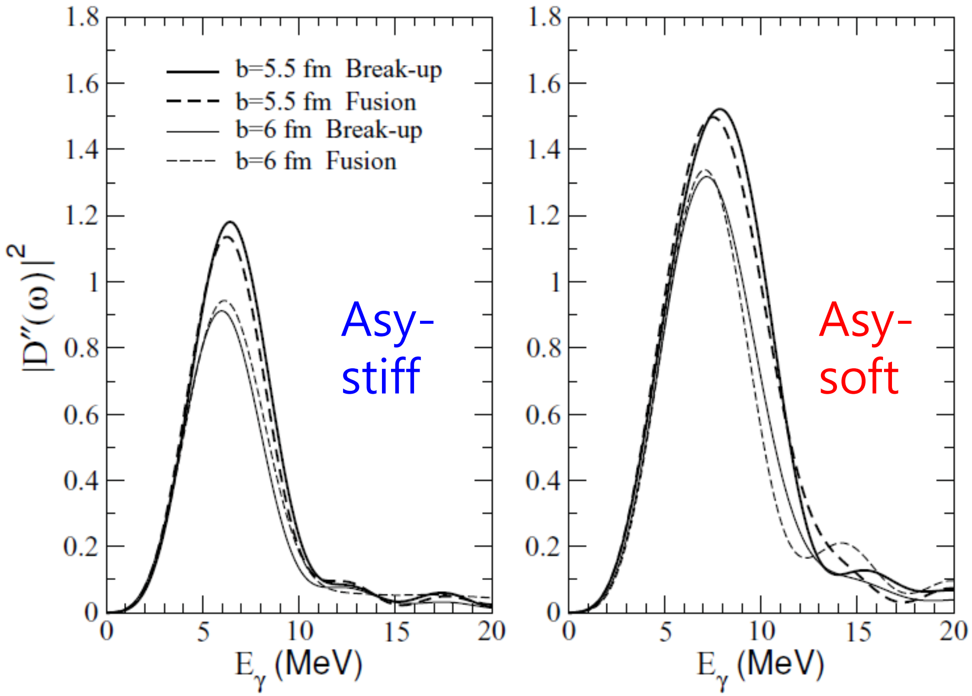
- Photon emission probability with $E_\gamma = \hbar\omega$

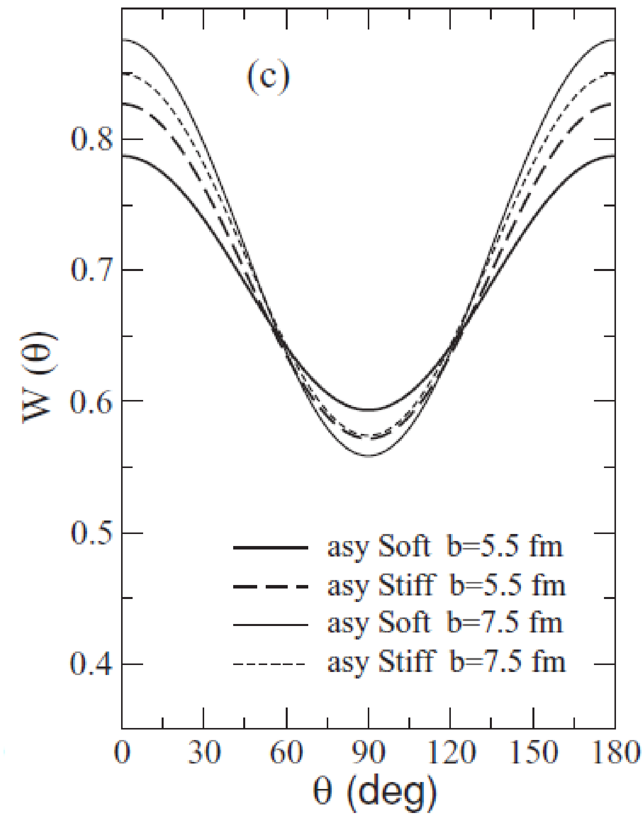
$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|D''(\omega)\right|^2$$

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

Dipole Emission in Fusion

$^{132}Sn+^{58}Ni$ @ 10 AMeV C. Rizzo et al., PRC 83, 014604 (2011)



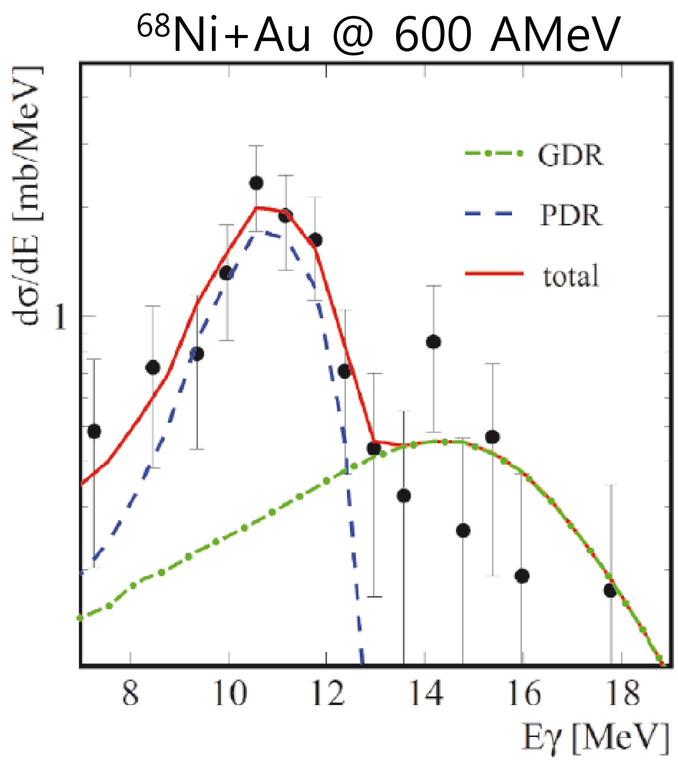


- More γ emission for Asy-soft
  - Fusion ≈ Breakup
- Stronger angular dependence for Asy-soft

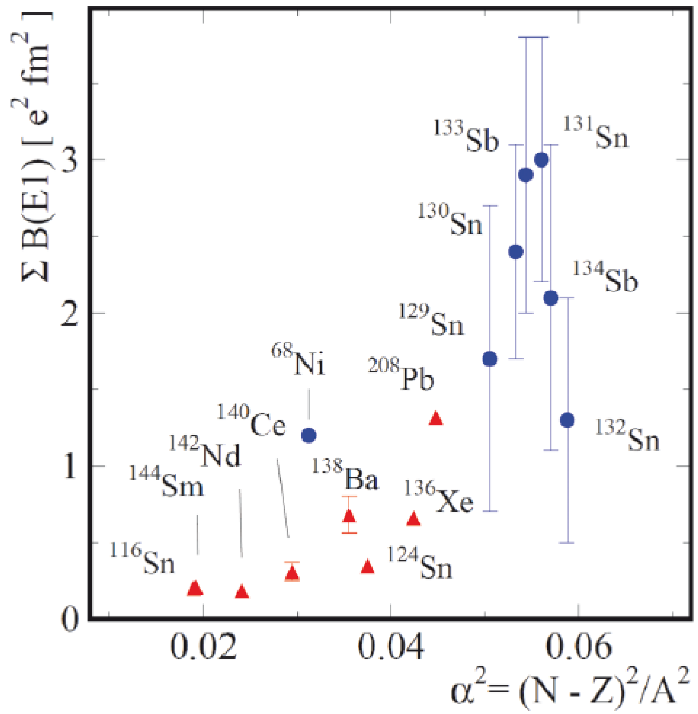
⇒ Larger E_{sym} at $\rho < \rho_0$ (Asy-soft) emits γ earlier with stronger θ asymmetry

Dipole Response at High Energies

O. Wieland et al., PRL 102, 092502 (2009)



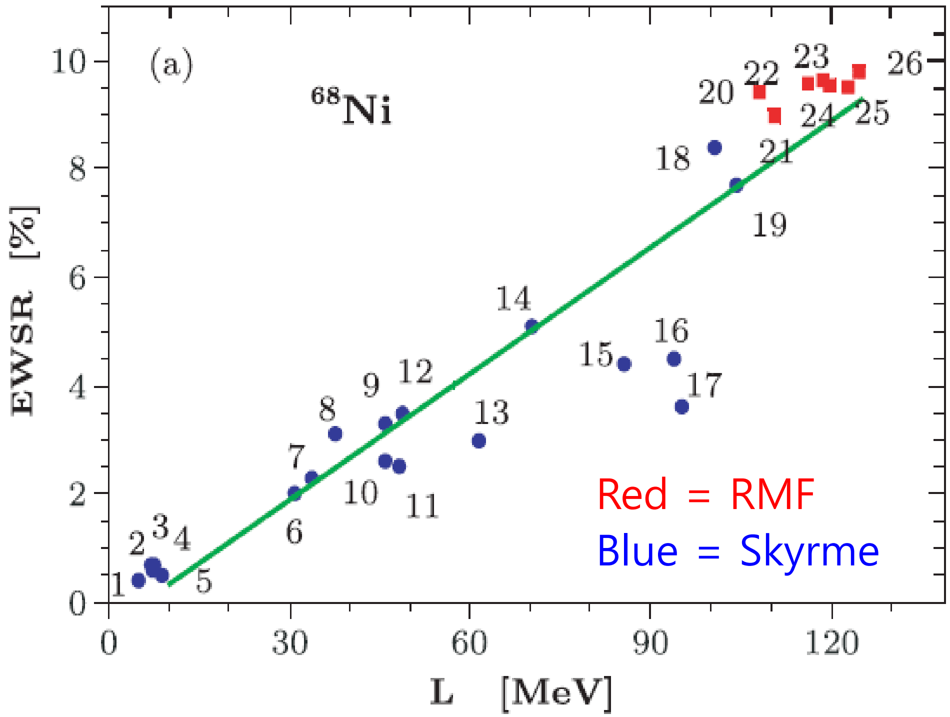
A. Klimkiewicz et al. (LAND), PRC 76, 051603 (2007)

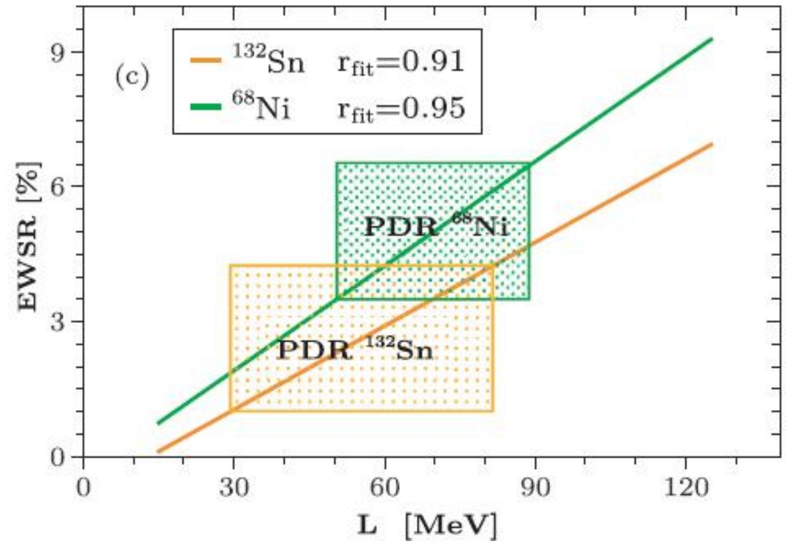


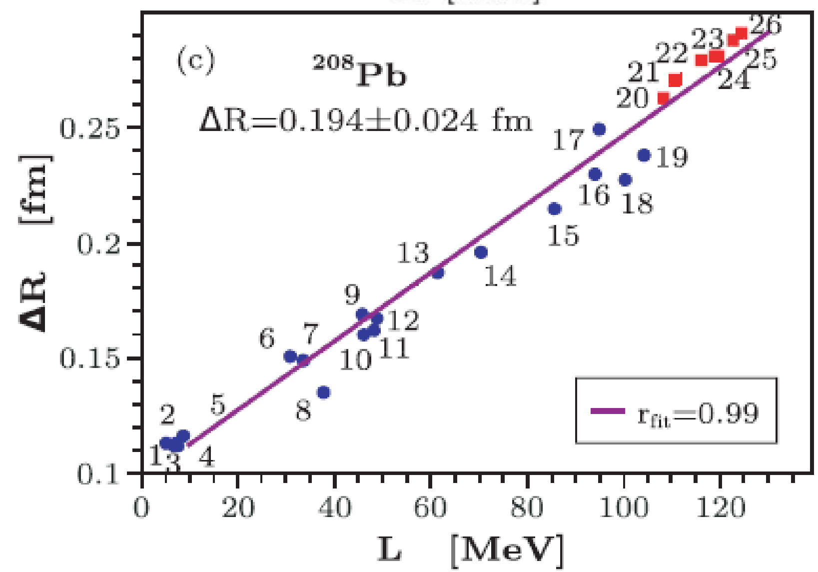
- Radioactive nuclei: Virtual photon absorption followed by neutron emission or by gamma decay
- The strength increases with the isospin asymmetry

PDR and Symmetry Energy

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







$$L = 64.8 \pm 15.7\ \text{MeV}$$

$$\Delta R \sim L\delta$$

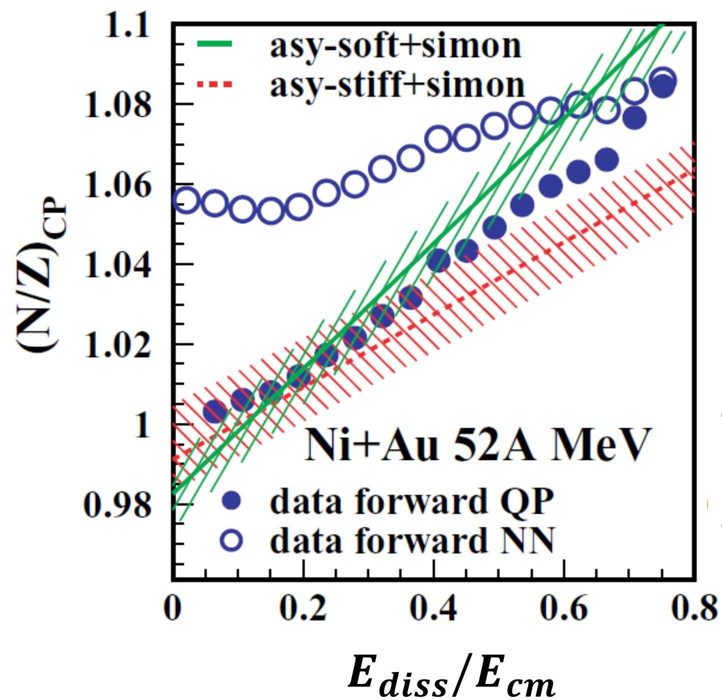
Charge Equilibration

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

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

  - 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)

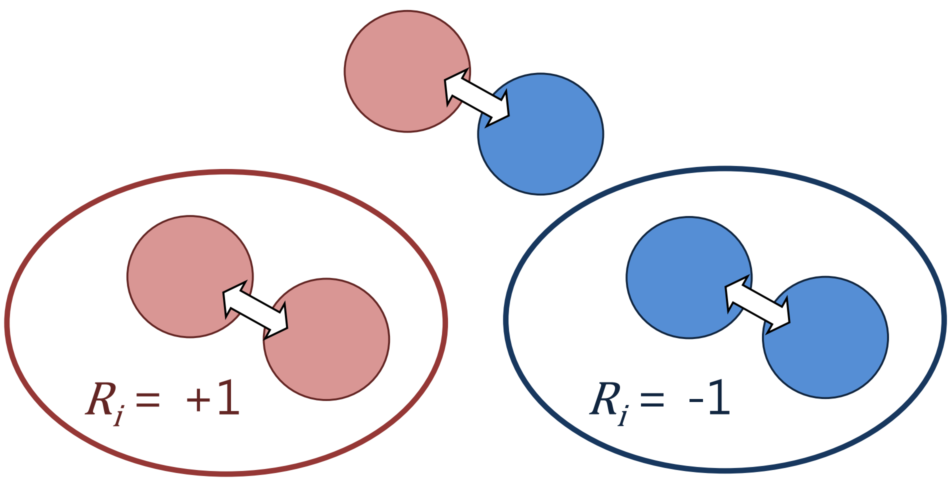
Isospin Transport/Diffusion

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

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

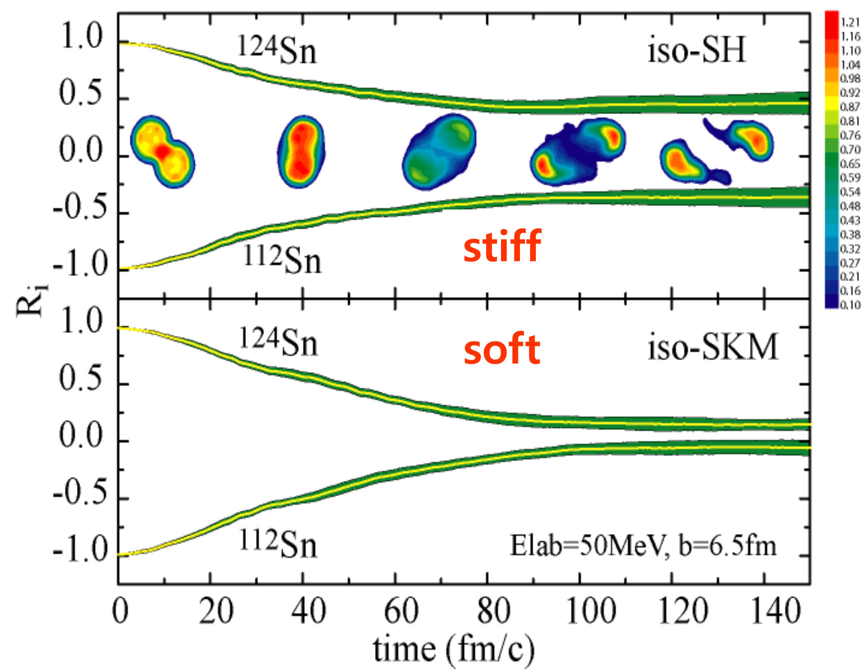
$$R_i = 2\frac{N^{AB} - (N^{AA} + N^{BB})/2}{N^{AA} - N^{BB}}$$

R_i = 0 for complete isospin mixing



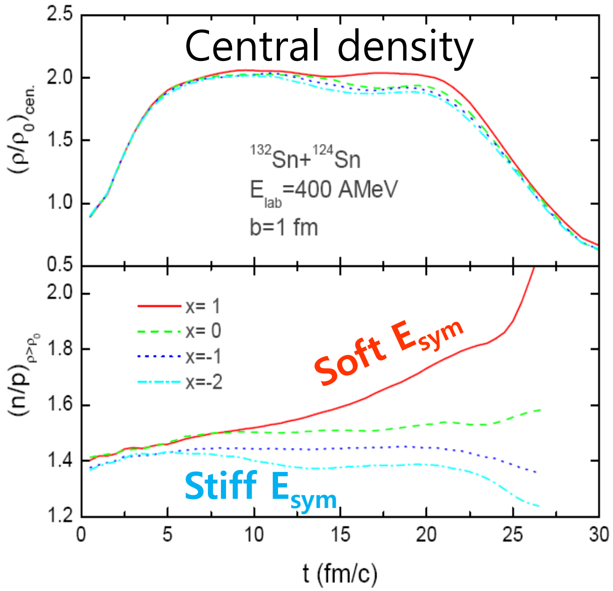
- Isospin diffusion occurs only in asymmetric collision system A+B

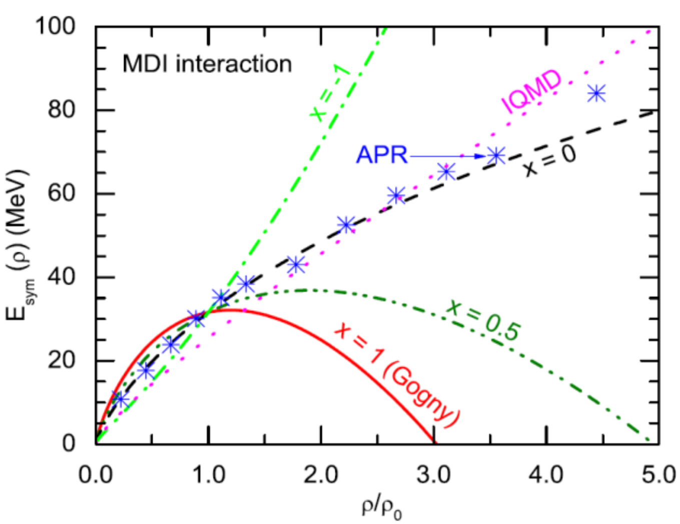
M.B. Tsang et al., PRL 92, 062701 (2004)



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

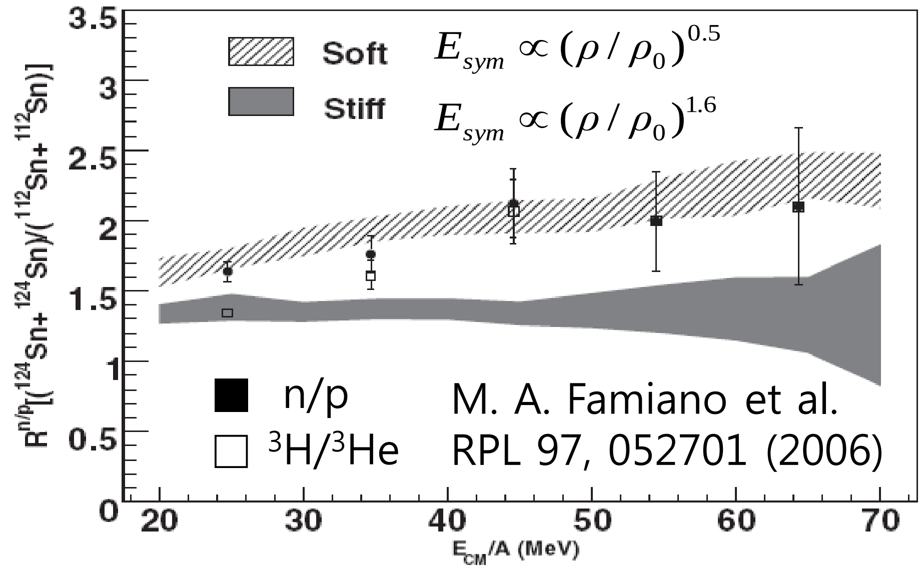
Particle Ratios



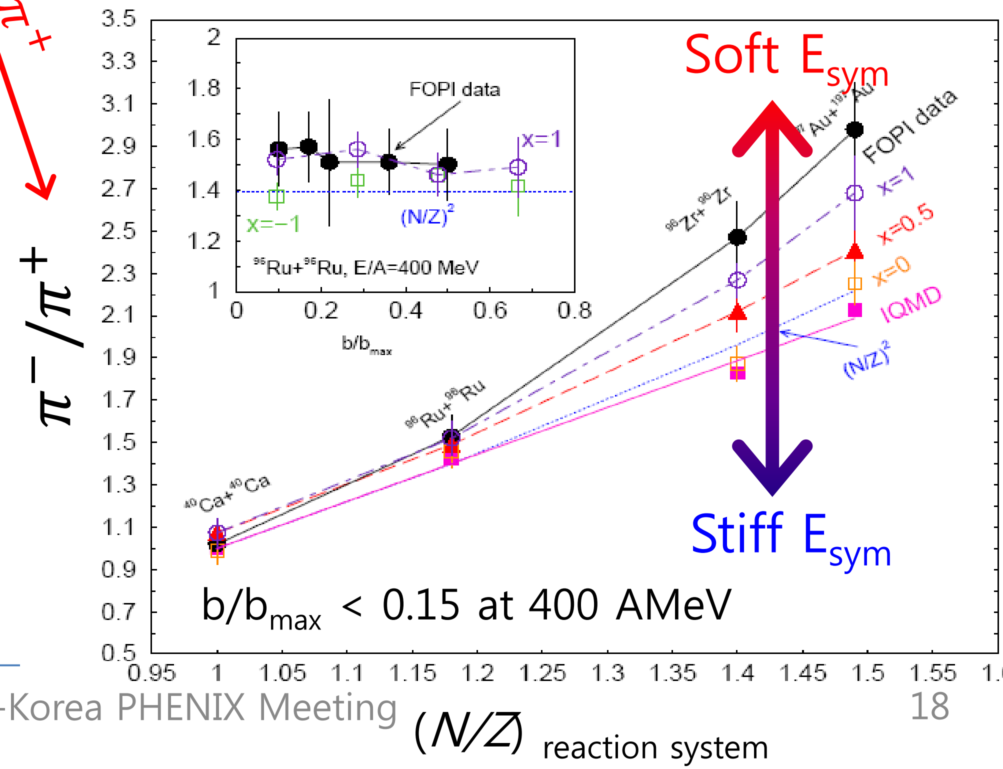


n/p
^{3}H/^{3}He
...

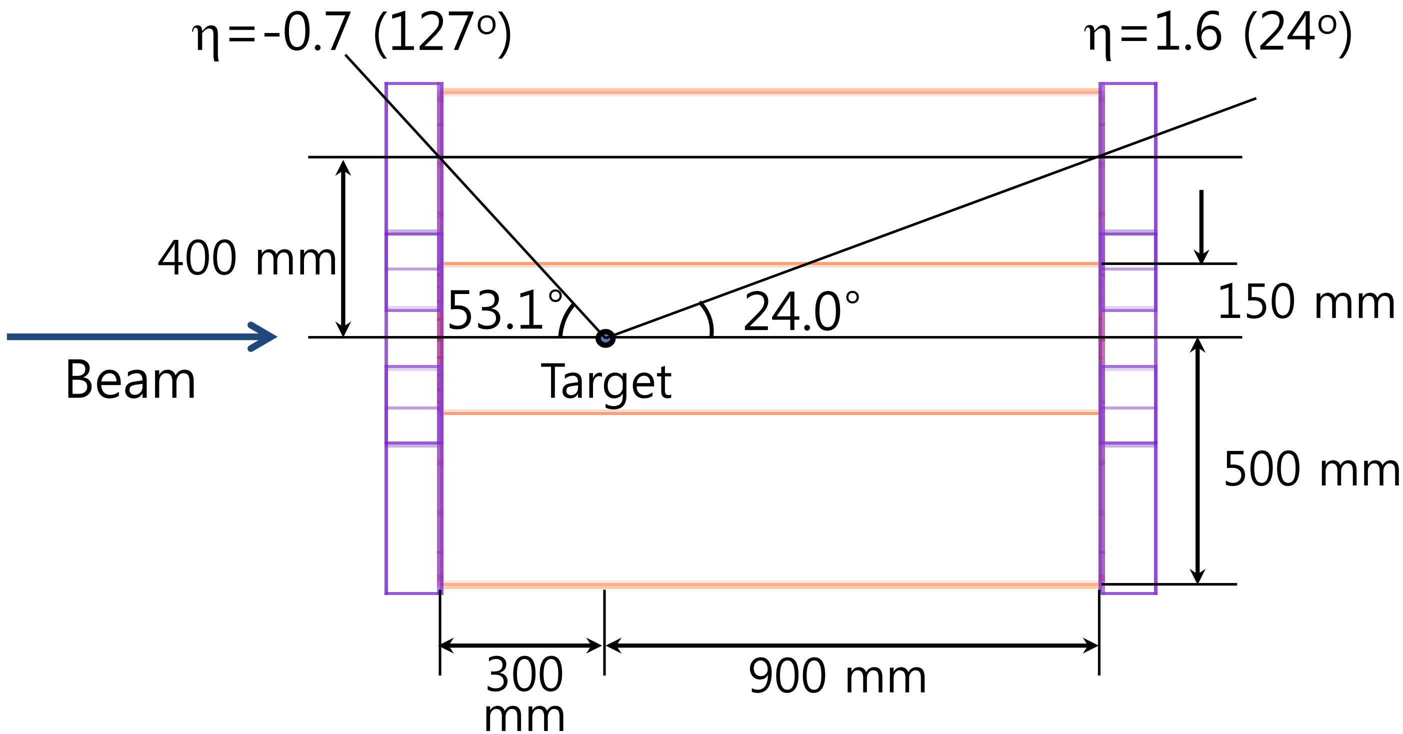
π^-/π^+



FOPI, Nucl. Phys. A 781, 459 (2007)



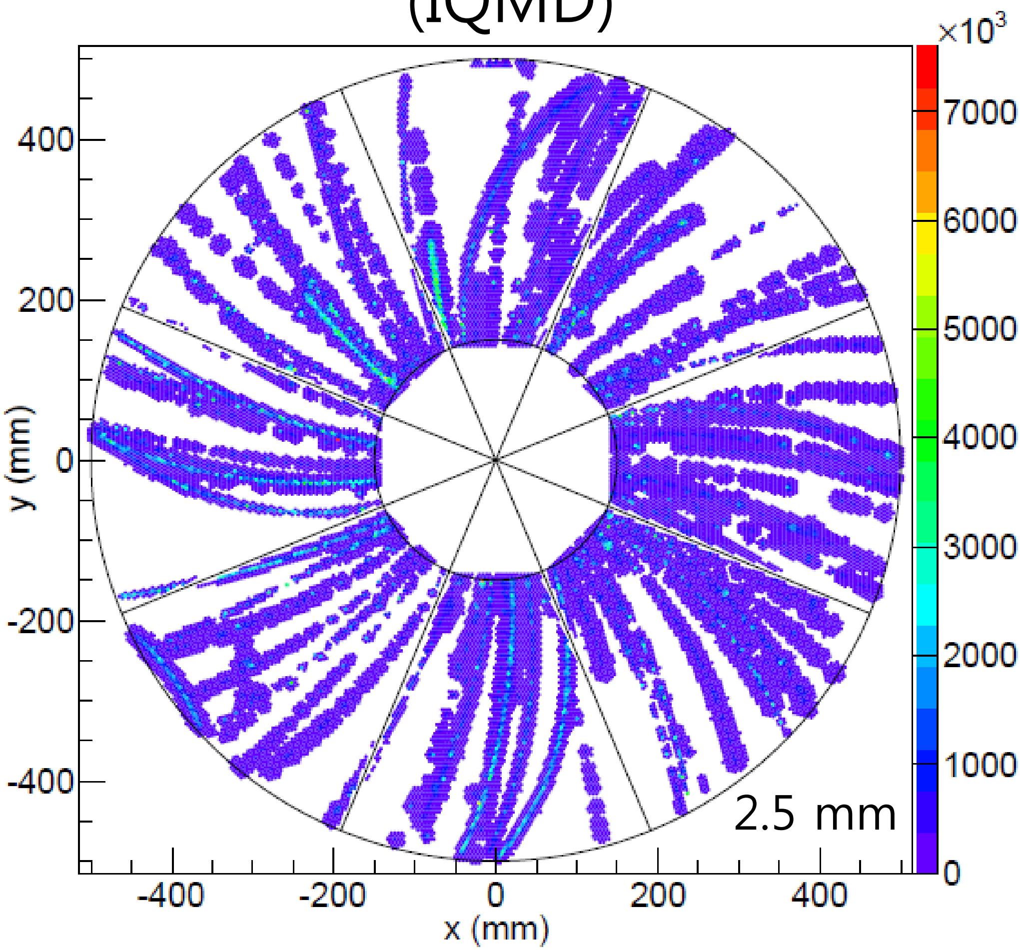
Time Projection Chamber



- Simulation with triple GEM readout using Garfield++
  - Gas mixture: Ar 90%+CO_2 10%, Voltage for each foil: 450 V
  - <Gain>~$1.4X10^6$, <Drift velocity>~50 mm/μs
  - <Dispersion> after 60 cm (maximum drift distance) < 3 mm

Time Projection Chamber

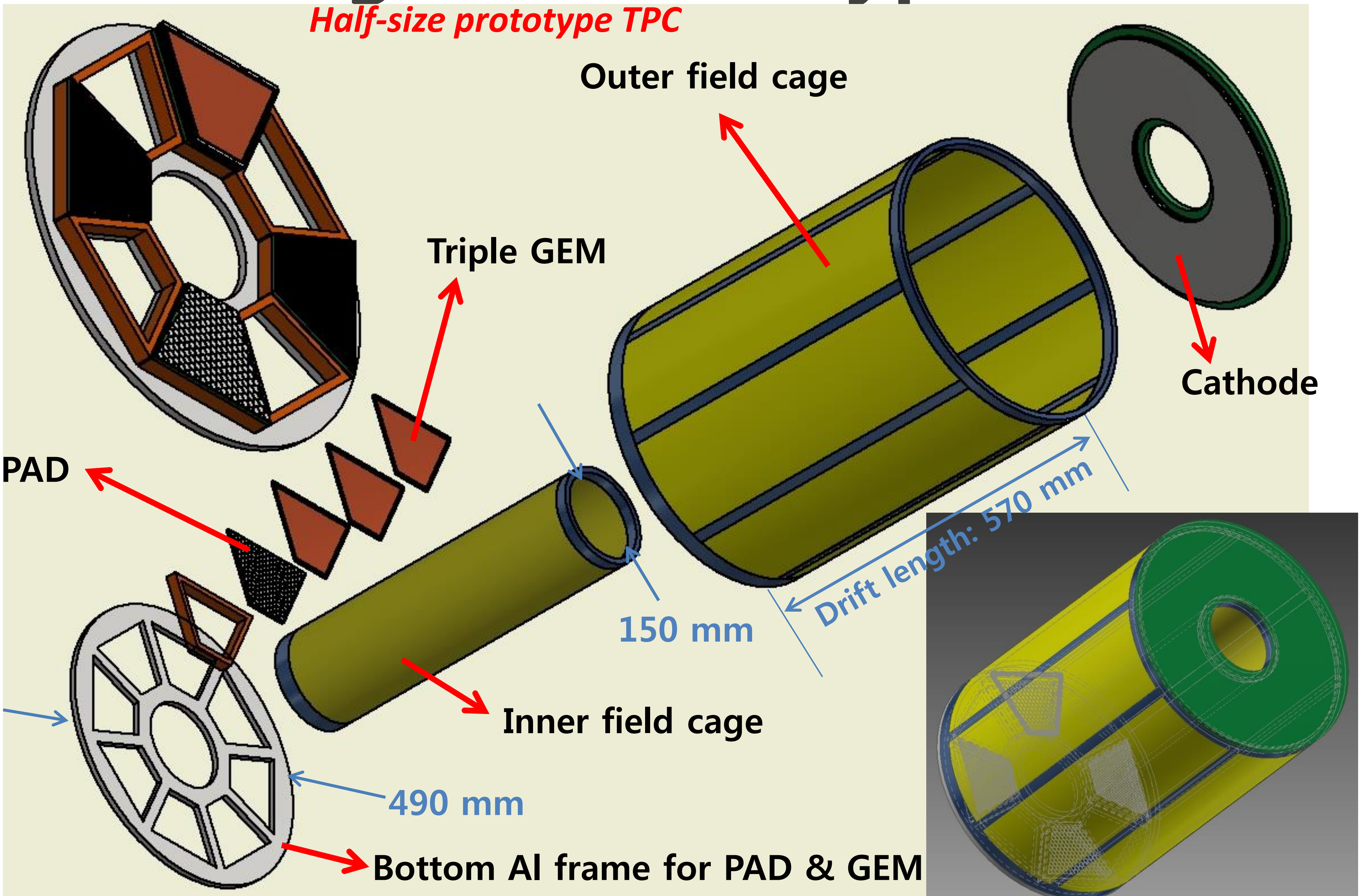
Central Au+Au at 250 AMeV (IQMD)



Color scale: the number of electrons in each pad

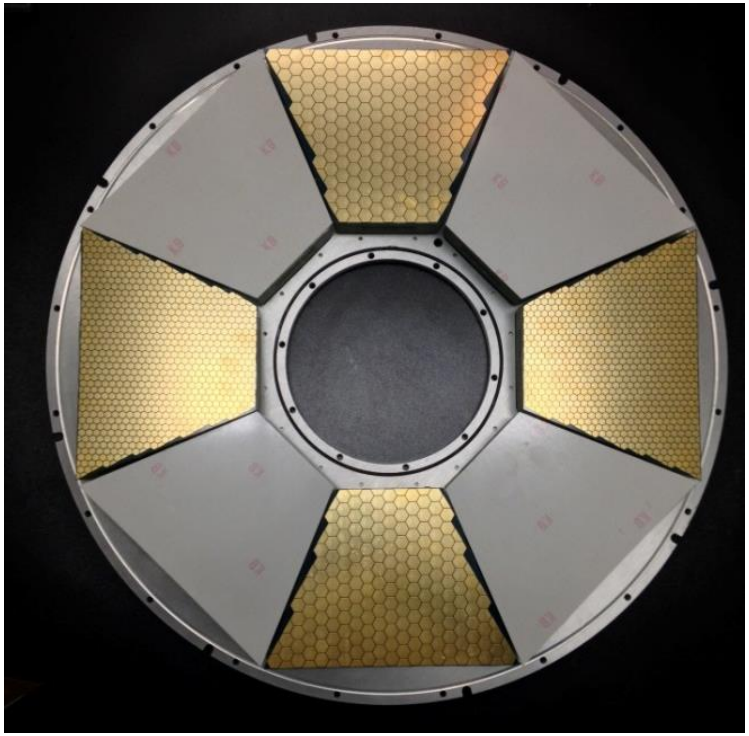
- Pad
  - Shape: hexagon
  - Total number of pads >20,000 for 5 mm
- Signal processing
  - GET: General Electronics for TPC

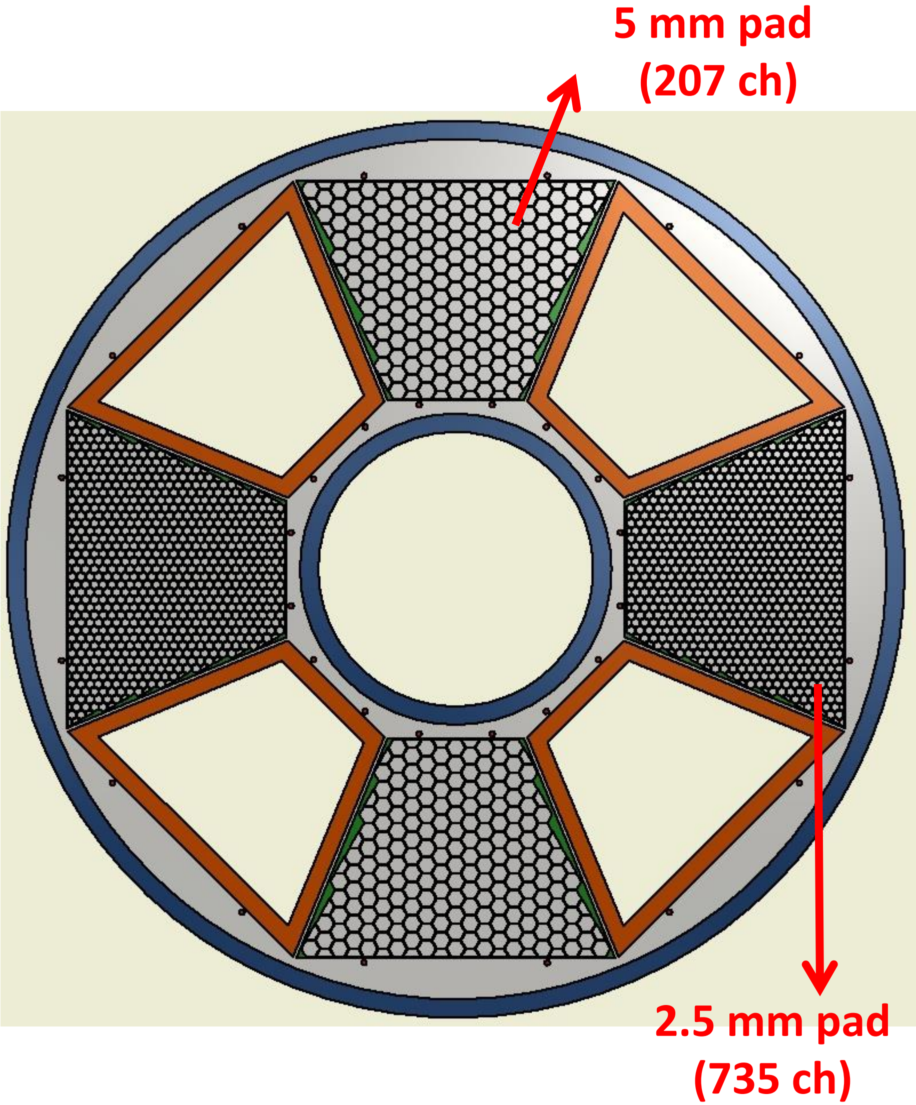
Design of Prototype TPC



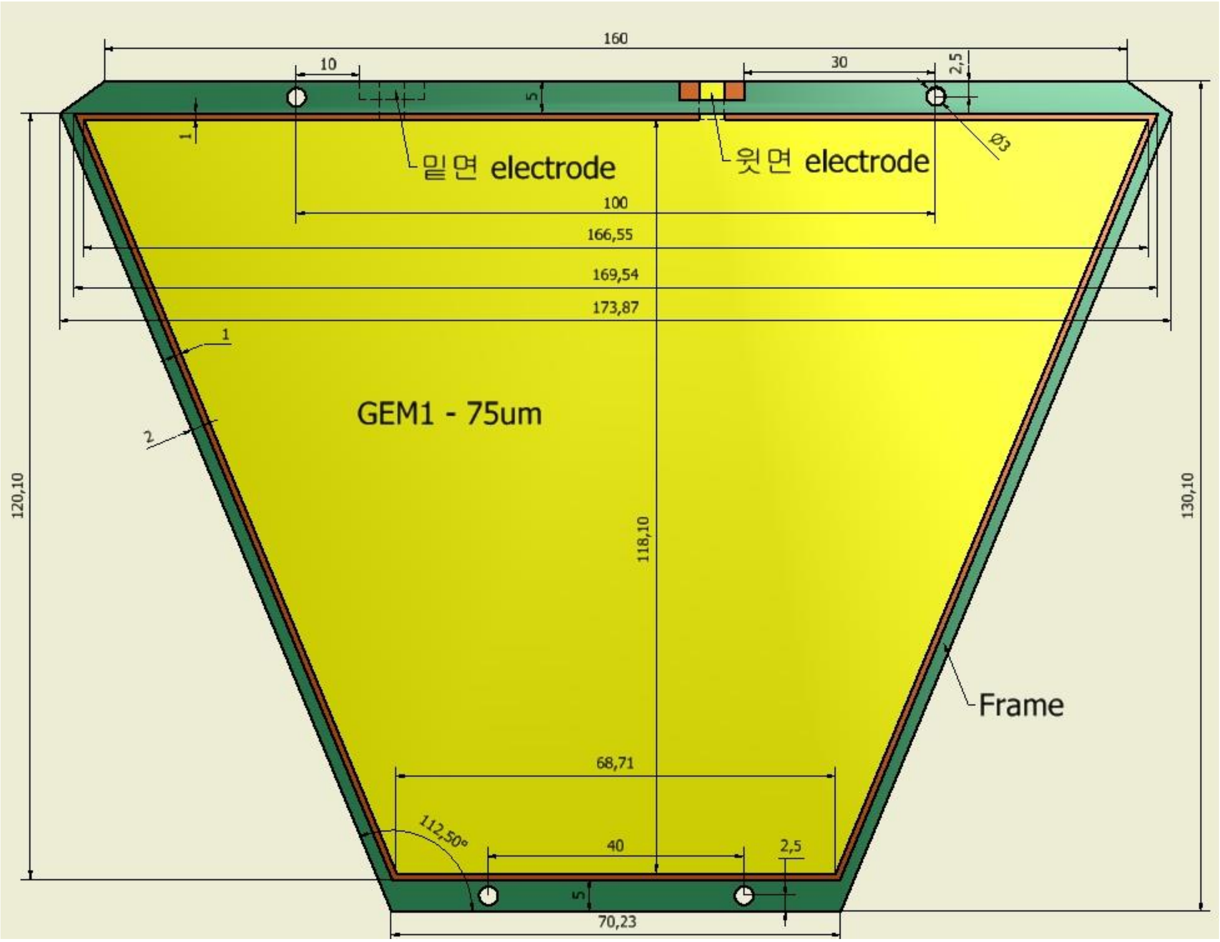
Prototype TPC-Pad Plane

- Hexagonal shape: 5 & 2.5 mm
- 500 μm gap between two pads
- Multi-layer PCB board
- 16 pin SMD type connectors

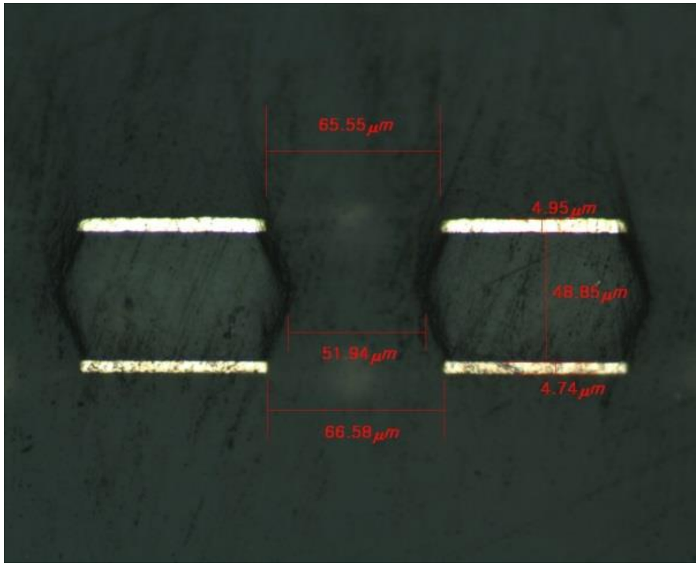




Prototype TPC-GEM

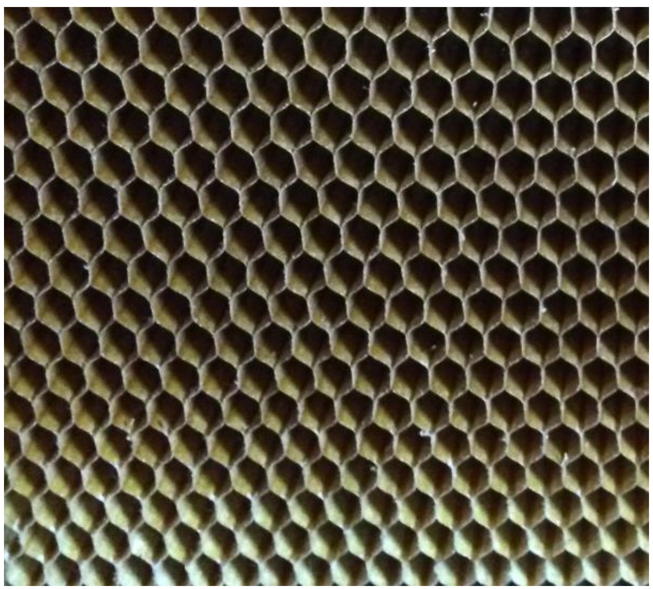


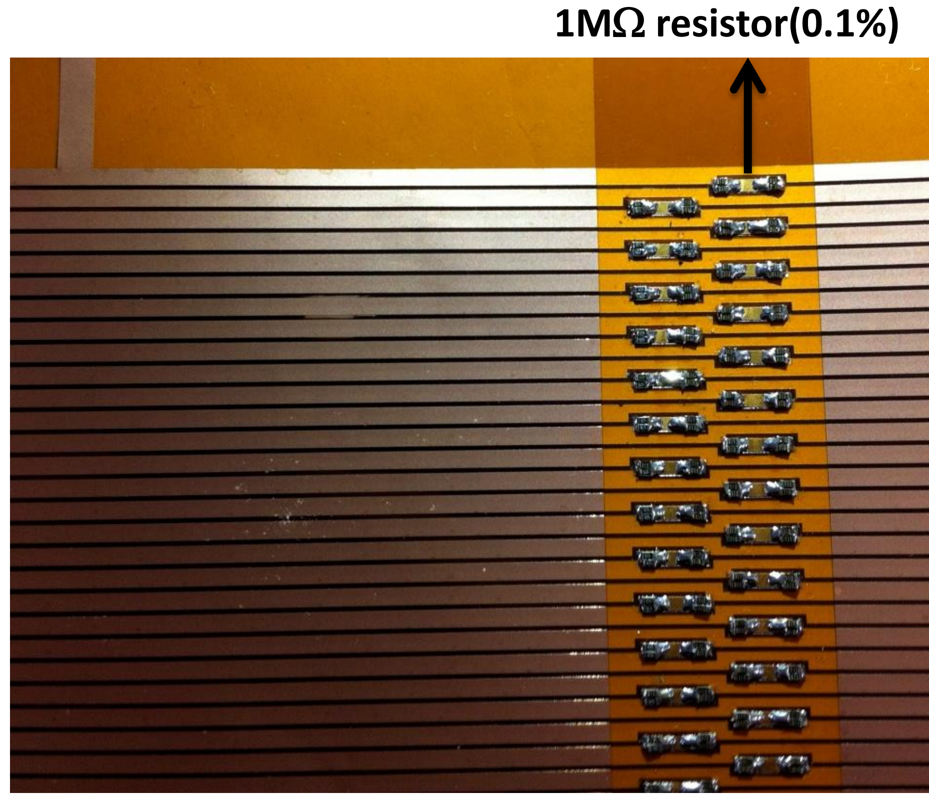
- Trapezoidal shape
- Thickness: 75 μm
- Area: 160X120 mm^2
- Triple layers for each pad



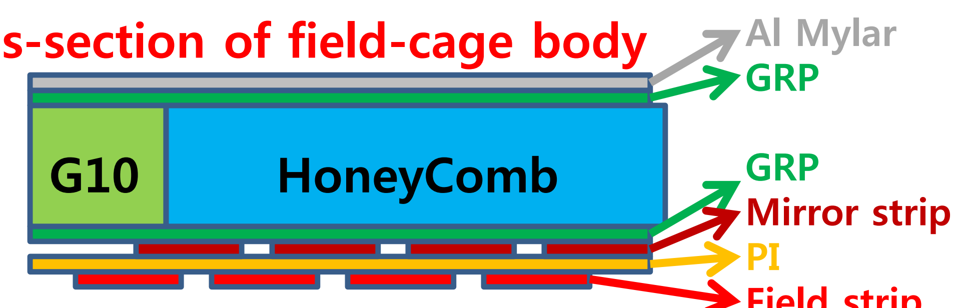
Prototype TPC-Field Cage

- 35 μm thick and 2 mm wide Cu strips
- 500 μm gap between adjacent strips
- Mirror strips on the back
- 1 MΩ resistors with 0.1% var.
- TPC body: G10 + Aramid honeycomb



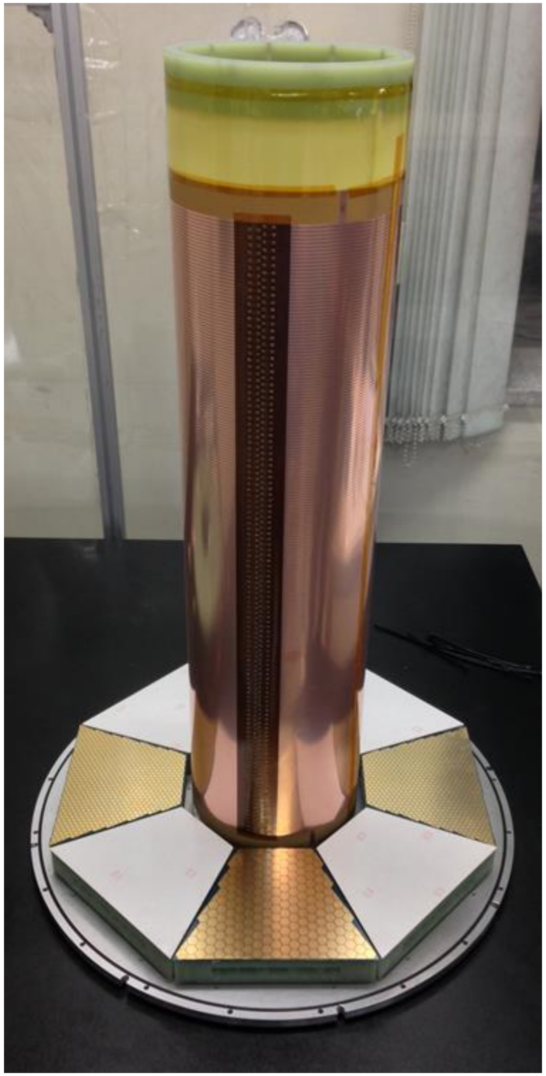


Cross-section of field-cage body

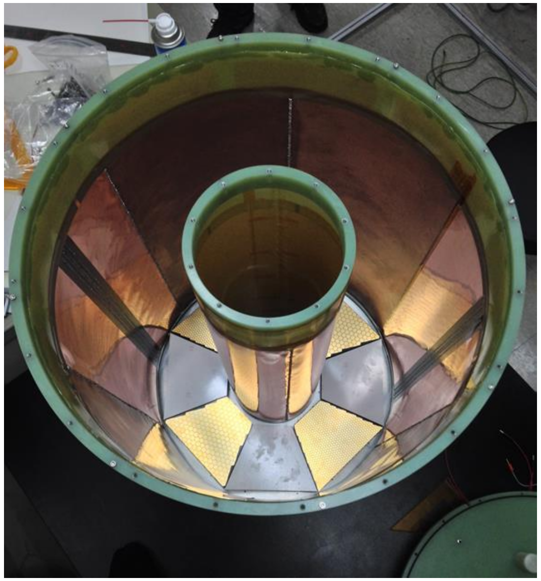


Prototype TPC-Assembly

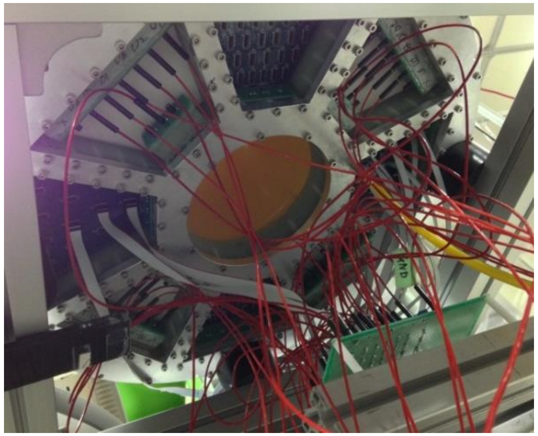
Inner Field Cage installed



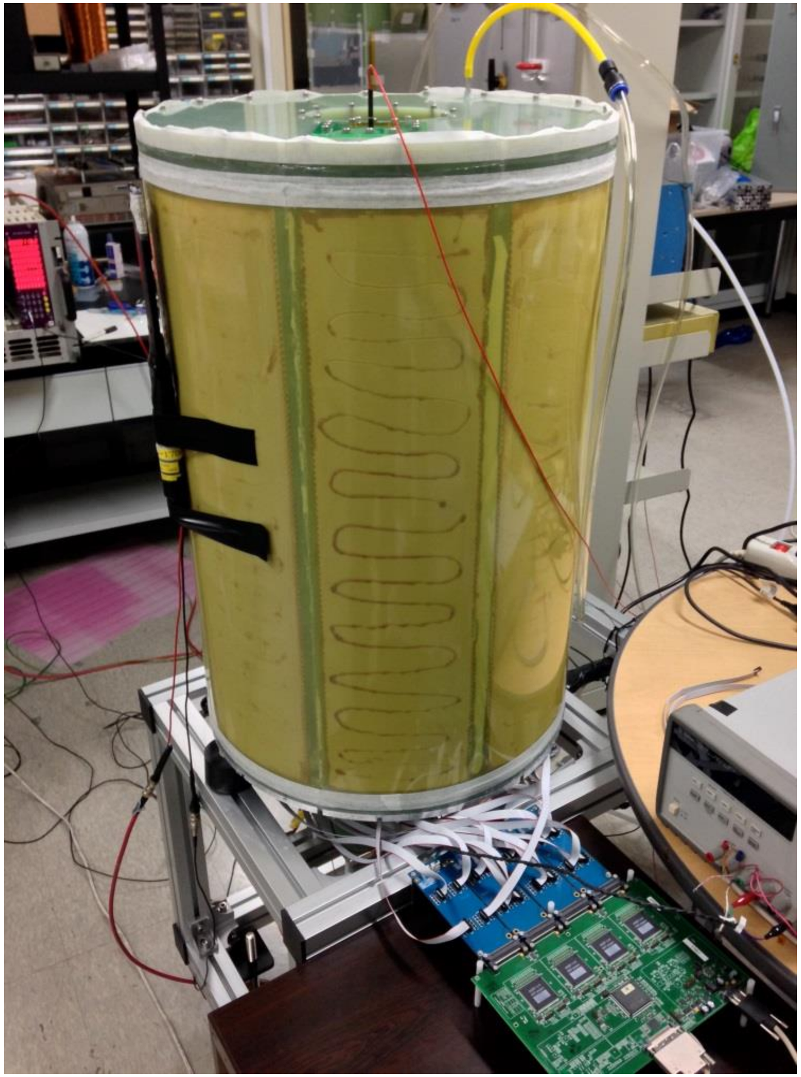
Outer Field Cage installed



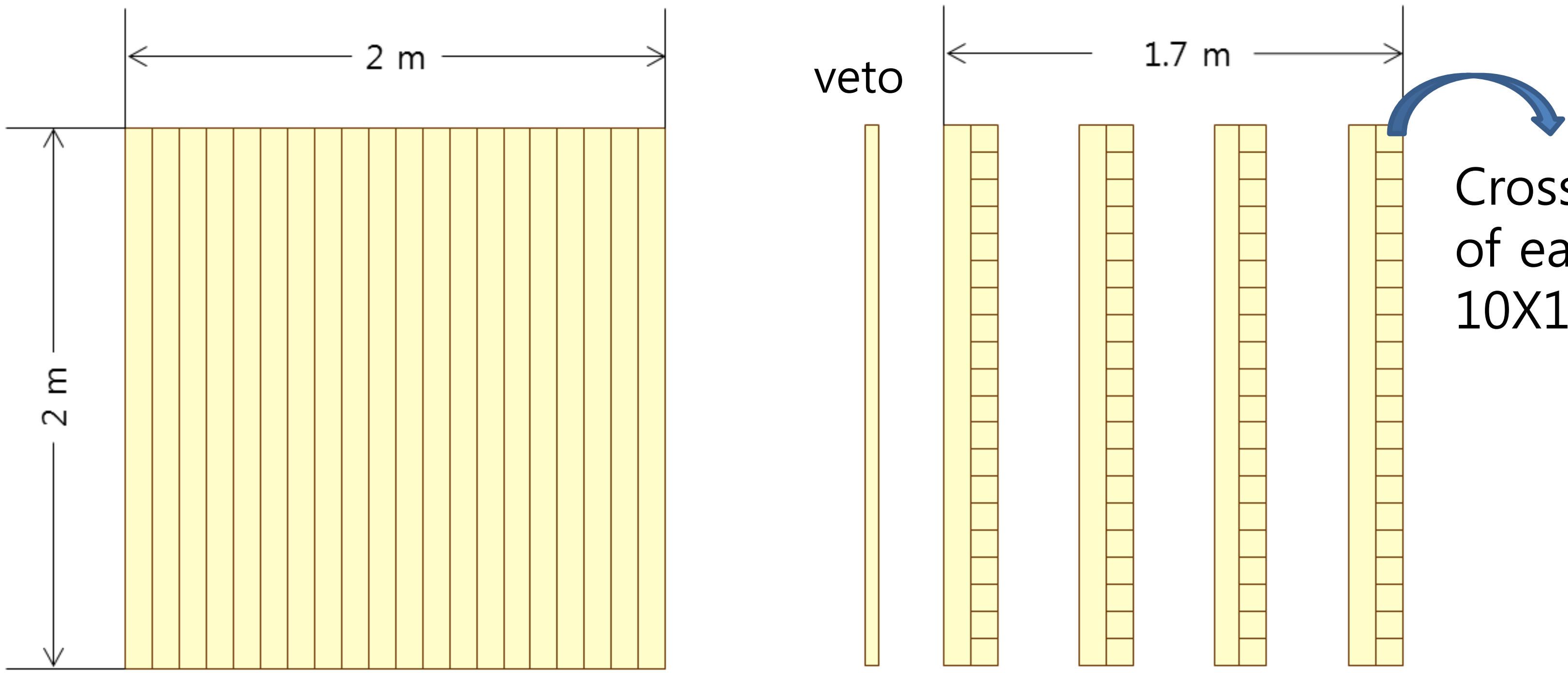
Prototype TPC : back



Prototype TPC assembled



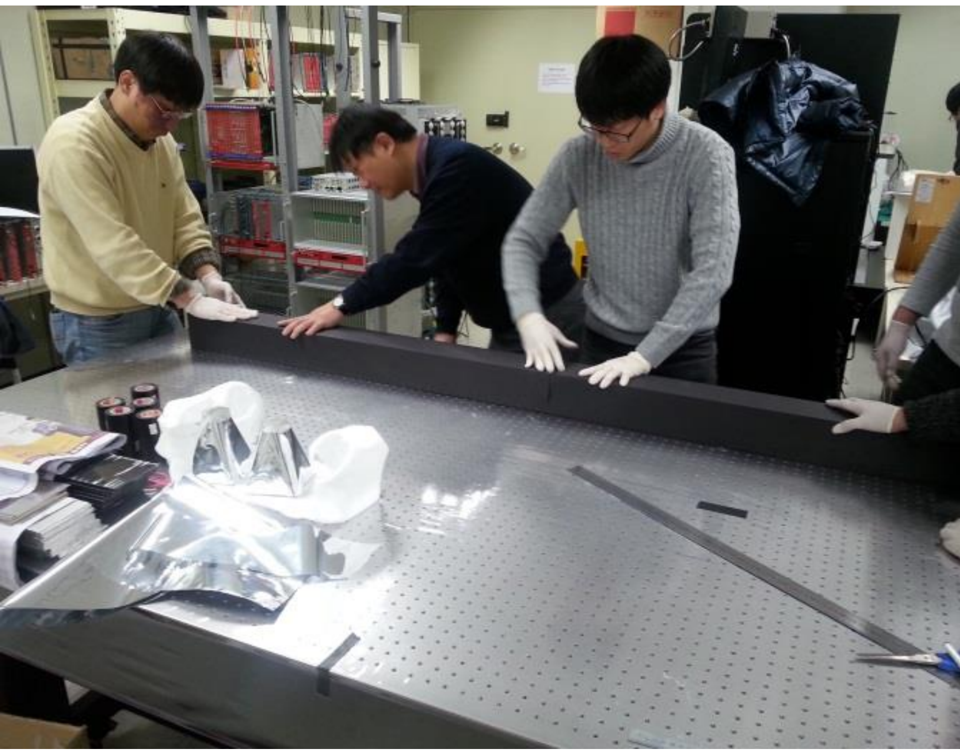
Neutron Detector Array

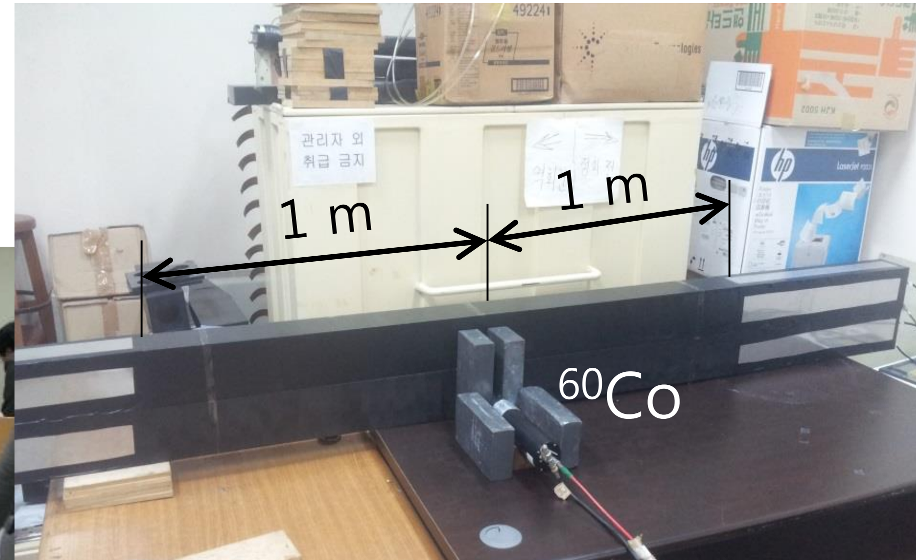


- Construction of the real-size prototype detector and test with radiation sources
  - Dimension: 0.1X0.1X2.0 m^3
  - Sources: ^{60}Co and ^{252}Cf

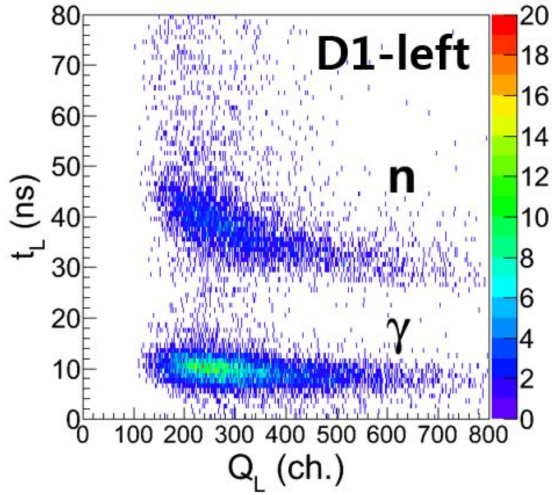
LAMPS-H Neutron Array

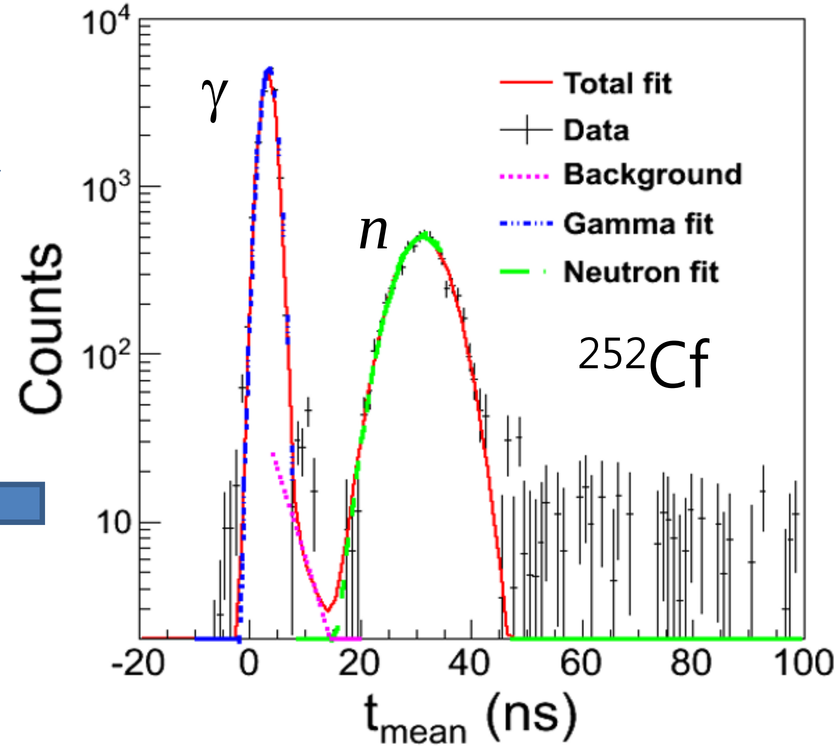
Assembly of the real-size prototypes (2 m long)

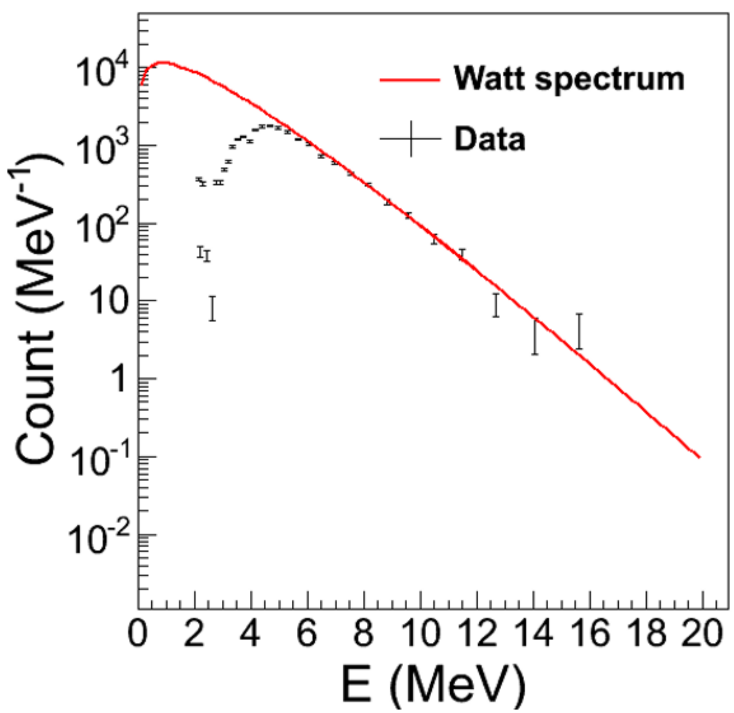




LAMPS-H Neutron Array







- 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)

Summary

1. RAON project
   - New opportunity will be in Korea for heavy-ion reactions with radioactive-ion beams.
   - First beam on target: ~2019 for LAMPS-L and ~2021 for LAMPS-H
2. KOBRA
   - Nuclear structure and astrophysics
3. LAMPS
   - Nuclear symmetry energy below and above ρ_0
   - Low- and high-energy LAMPS setups to be constructed.