Large Acceptance Multipurpose Spectrometer AT KoRIA for Symmetry Energy Researches

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On behalf of
Nuclear Matter Research Group

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Contents

1. Introductions

1. High-intensity RI beams by ISOL & IFF
   - 70 kW ISOL from direct fission of ^{238}U induced by 100-MeV S. C. cyclotron proton beam with the current of 1 mA
   - 400 kW IFF RI by using 200 MeV/u ^{238}U with a maximum 8pμA

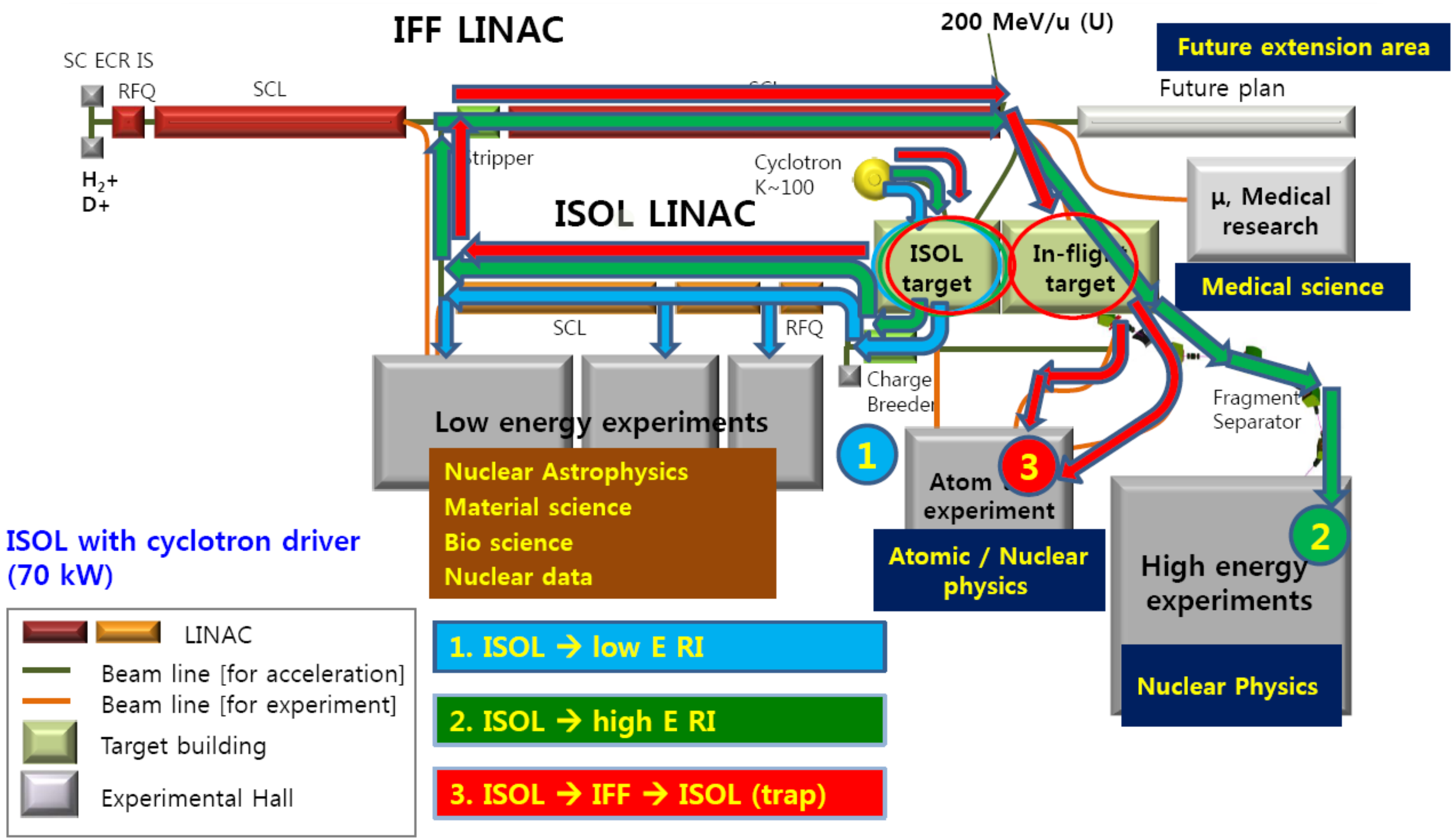
2. High-energy, high-intensity neutron-rich RI beams
   - ^{132}Sn (double magic) at maximum E of ~250 MeV/u up to 9×10^8 pps

3. Various exotic RI beams by using ISO+IFF RI production processes

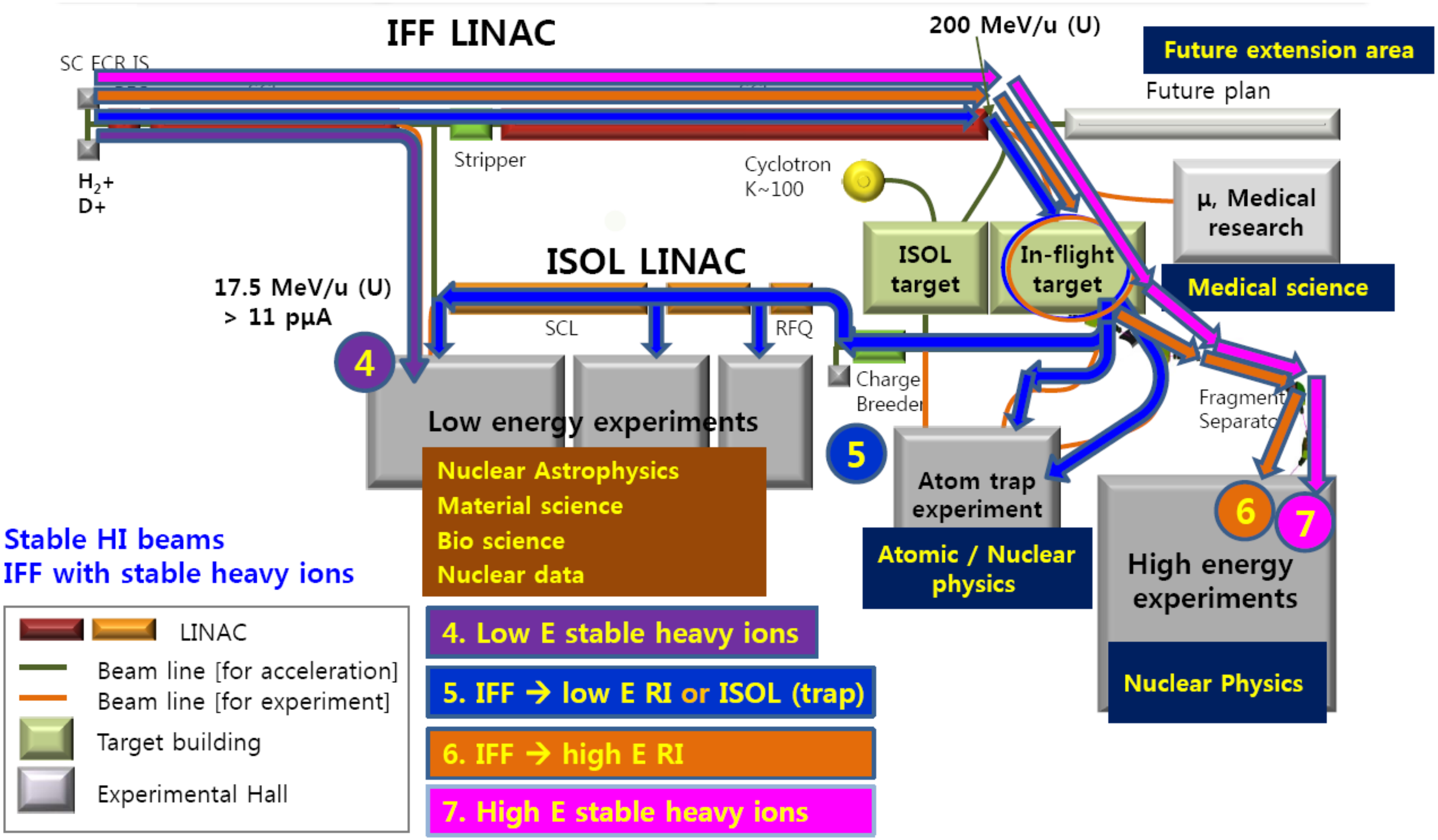
4. Need a design of a facility to adapt various exotic experiments in nuclear physics
   - Should be designed for maximal use
     (More statistically precise measurements proposed in FRIB & RIBF)

5. Facility: available for upscope.

- ISOL RI: K100 proton cyclotron → ISOL → ISOL LINAC → IFF main LINAC → High energy experiments (2)



- IFF RI: SC ECR → IFF Main LINAC → In-flight target → Fragment separator → High energy experiments (6)
- Stable HI: Main LINAC → High energy experiments (7)



2. Physics proposed in the KoRIA Symm.E group

Equation of state (EOS) of neutron-rich nuclear matter at low & high density up to $\rho \sim 3\rho_0$ (?)

1. **Probing E_{sym} of neutron-rich matters at a wide range of density from neutron-rich HI collisions**
2. **Understanding astronomical phenomena in neutron stars, black holes, and super novae by the EOS of nuclear matter at high density**
3. **Nuclear synthesis**
4. **Exotic nuclei lying near neutron drip lines**

Nuclear Equation Of State (EOS) of nuclear matter in the isospin space

$$E(\alpha,\rho) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + o(\delta^4)$$

symmetry energy

Energy in symmetric matter

Energy per nucleon

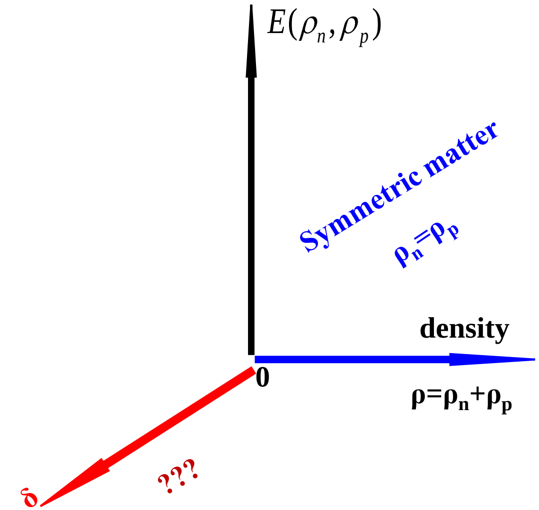
$$\delta \equiv (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

ρ_n : neutron density

ρ_p : proton density

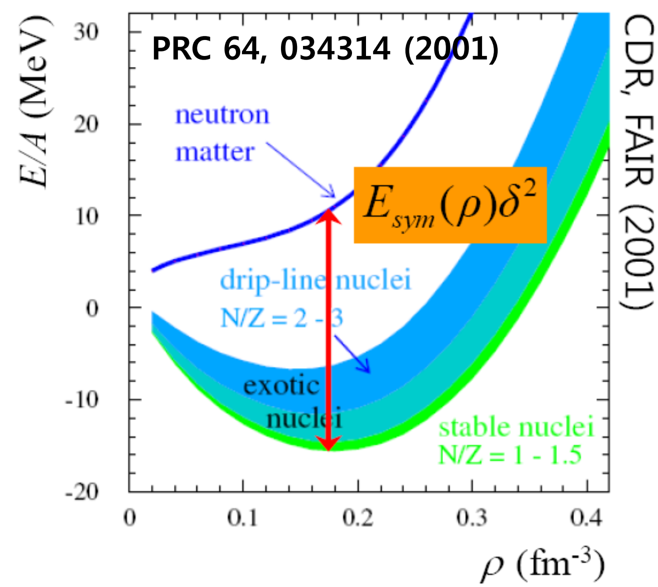
ρ_0 : Saturation density

Nucleon density $\rho = \rho_n + \rho_p$



$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\delta)}{\partial \delta^2}\bigg|_{\delta=0} \qquad E_{sym}(\rho_0) \sim 30\,\mathrm{MeV}$$

$$E_{sym}(\rho) \simeq E(\rho,\delta=1) - E(\rho,\delta=0)$$



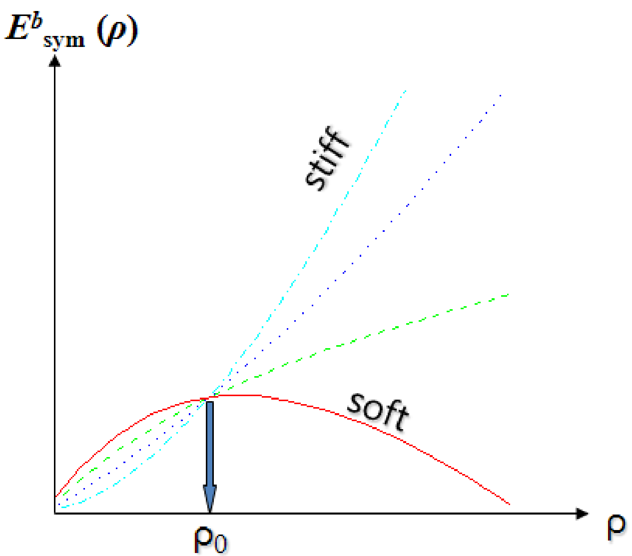
Model predictions for E_{sym} at high nuclear matter density

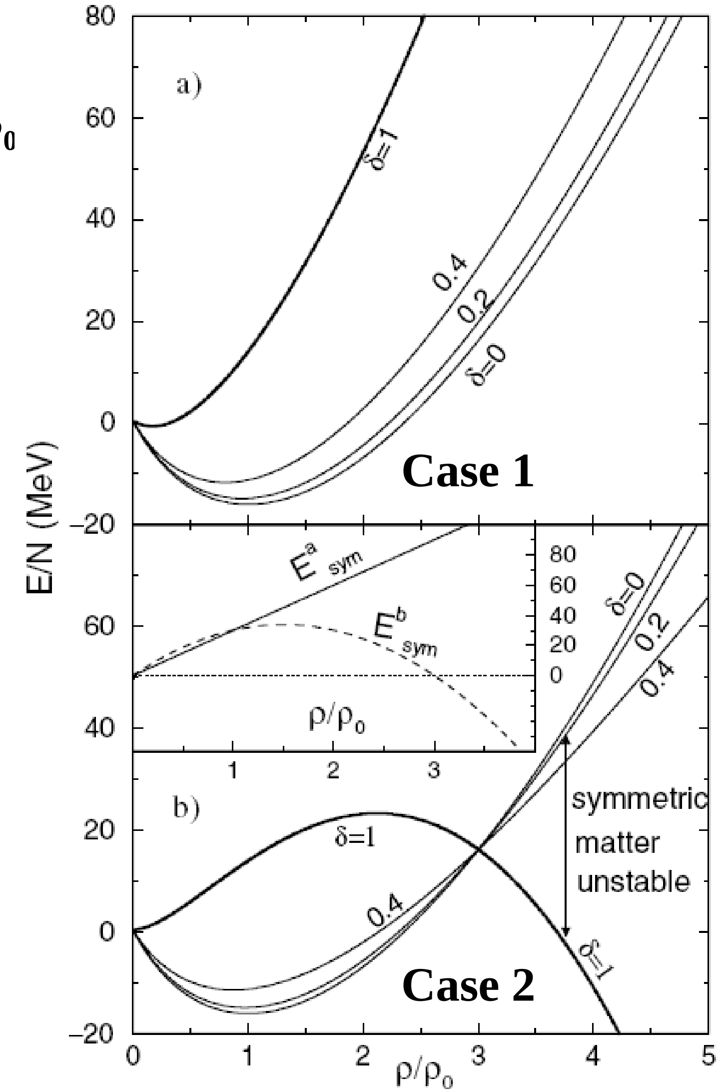
Case 1: $E^{a}_{sym}(\rho) = E_{sym}(\rho_0)\, u, \;\; u = \rho / \rho_0$

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

B. A. Li, PRL **88** 192701-1 (2002)

B. A. Li , *et al.*, Phys Rep. **464** 113 (2008)





Experimentally we observe phenomena...

1. Signals at sub-saturation densities appeared in collision data
 - Sizes of neutron skins for unstable neutron-rich nuclei
 - n/p ratio of fast, pre-equilibrium nucleons
 - Isospin fractionation and isoscaling in nuclear multifragmentation
 - Differential collective flows of n and p
 - Isospin diffusion
 - Correlation function of n and p
 - $^3H/^3He$ ratio in rapidity, etc.

2. Signals at above saturation densities appeared in collision data
 - π^-/π^+ ratio
 - Differential collective flows of n and p
 - Azimuthal angle dep. of n/p ratio w.r.t. the reaction plane
 - Correlation of various observables

- **다수의 파쇄핵 발생시 isospin fractionation, isoscaling, isospin diffusion**
  Isospin-dep. of EOS (^{132}Sn+^{132}Sn, ^{124}Sn+^{124}Sn), B. Li, Phys Rev Lett 85 4221 (2000)

- **발생하는 중성자와 양성자의 미분 집단 흐름(differential collective flow, B.-A. Li, PRL 85, 4221(2000), (Ru-96, Zr-96: PRL84 1120, 2000)**

- **종방향 편극도에 따른 π^- 및 π^+ 발생 분포 및 비율**
  At SIS/GSI, W. Reidorf. et al., Nucl Phys A 781 459 (2007) (^{197}Au+^{197}Au)

- **충돌 반응면(reaction plane) 상에서 중성자와 양성자의 발생비의 방위각 의존성 (azimuthal angle dependence)**

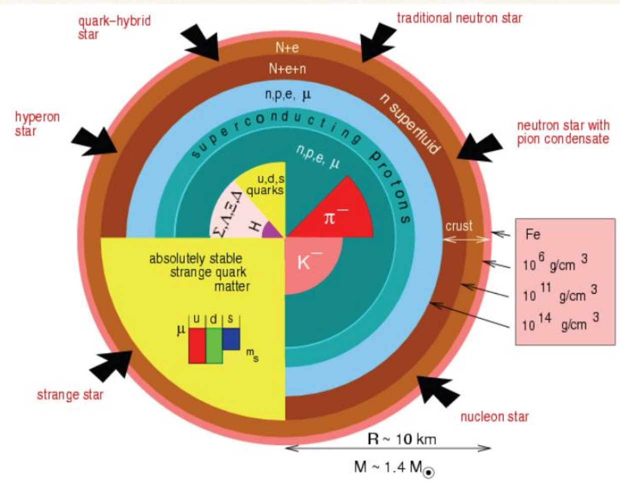
- **EOS와 중성자 과잉핵의 중성자 핵껍질 구조**
  (^{132}Sn+^{208}Pb, IFF from ^{238}U beam, GSI)
  Neutron skin of ^{132}Sn & ^{68}Ni : A. Carbone et al., Phys Rev C 81 041301 (2007)
  Neutron skin of $^{129\sim132}$Sn, $^{133\sim134}$Sb A. Klimkiewicz, Phys Rev C 76 051603 (2007)

- **Neutron drip line 근처의 rare isotope**
  (MoNA-LISA/FRIB)
  First evidence of ^{18}B : Phys Lett B 683 129 (2010)
  First observation of ^{12}Li* : Phys Rev C 81 021302R (2010)
  Evidence of double magic ^{24}O : Phys Lett B 672 17 (2009)

From theory group

1. Neutron-rich nuclei 포화 핵물질 밀도에 따른 대칭 에너지의 변화의 전반적 연구

- 포화 핵물질 밀도 이하에서 GMR, neutron skin thickness 등 이론적 계산
- Neutron-rich nuclei 강입자의 질량, 전자기적 형태 인자 등 특성 연구
- 유효장 이론, 쿼크 모형, 격자 양자색역학 등을 이용 RI 내 핵자 간 상호작용 연구



2. 중성자별에 대한 전반적 이론적 연구

- 대칭에너지 이용 중성자별 내부를 구성하는 입자의 종류, 구성비 계산
- 중성자별 크기, 질량 계산 결과 대칭 에너지의 밀도 변화를 결정하는 주요 변수를 결정
- 포화 핵물질 밀도 이하의 상태 방정식 이용 중성자별의 껍질 구조 연구
- 초강력 전자기장이 중성자별의 특성에 미치는 영향에 대한 연구

3. 중성자별과 블랙홀이 포함된 거대 천체 현상에 대한 핵물리학적 연구

- 중성자별-중성자별의 충돌, 중성자별-블랙홀의 충돌 과정에서 방출되는 에너지 계산

4. Parity, time reversal 등이 위배되는 현상과 이러한 현상에 연관된 상호작용에 대한 연구

- Even 또는 odd parity를 갖는 방사성 동위원소의 전자기적 전이 과정을 통해 중성자가 많은 환경에서 핵자 간 약한 상호작용의 형태와 결합상수를 결정

5. 핵자 스핀에 대한 탐침과 스핀에 의해 결정되는 물리량에 대한 이론 및 실험 연구

연구의 중요도 순위

1. Neutron-rich matter에서 포화 핵물질 밀도보다 큰 밀도에서 EOS에 대한 연구

- 최대 250 MeV/u의 에너지를 갖는 RI beam 이용 충돌계에서 양성자, 중성자, 파편핵, π^+, π^-등을 측정하여 포화 핵물질 밀도 이상에서 대칭에너지의 밀도 의존성 연구

2. 다수 중성자 원자핵을 이용한 포화 핵물질 밀도 이하에서 물질의 상태방정식에 대한 연구

- 포화 핵물질 밀도 이하에서 대칭에너지의 밀도 의존성 연구
- GMR, neutron skin thickness 등을 이론적으로 계산하고 실험에서 측정하여 대칭에너지를 결정하는 주요 변수를 결정하는데 기여

3. 최대 300 AMeV stable HI 충돌 실험을 통해 물질의 상태방정식에 대한 연구

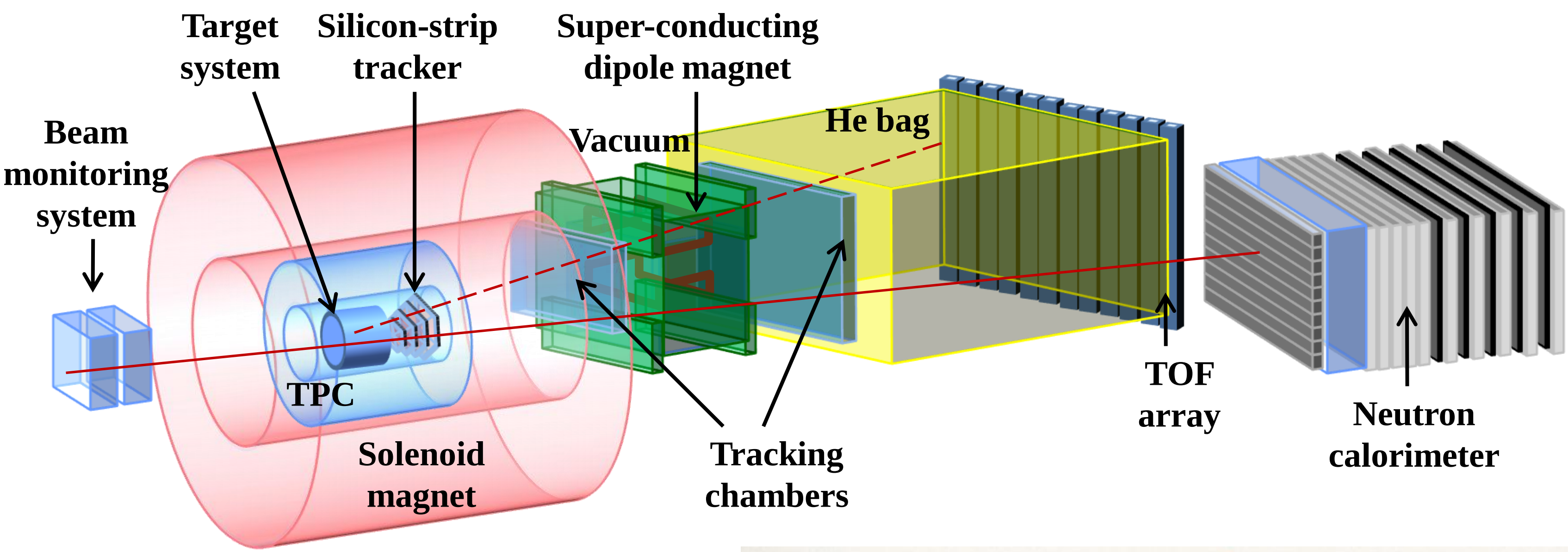
- p, n, 및 light fragment들의 생성량과 운동량 분포, collective flow, 반응면에 대한 n/p 발생 각분포 연구 (RI 실험결과를 이해하기 위하여 중요한 reference data 역할을 함)

상기 연구 목적을 달성하기에 적합한 다목적 분광기 및 검출장치의 개발이 요구됨.

→ Large Acceptance Multipurpose Spectrometer (LAMPS)

3. Design of LAMPS

LAMPS for Symm.E



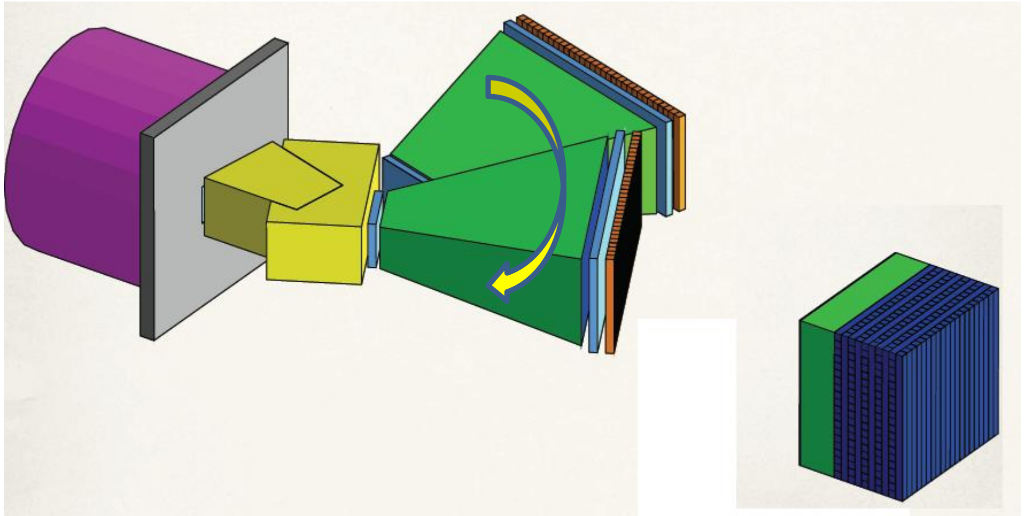
- Solenoid magnet
  + TPC
  + silicon-strip tracker

  ~ 3 π Sr

- Dipole magnet
  + tracking chambers
  + TOF array

  ~ 30 mSr

- Neutron calorimeter at +- 8º   50 mSr



Detectors in LAMPS

Solenoid with B = 1 T & TPC

- Acceptance ~ 8 Sr for π^+, π^-, p, n, d, t, ^{3}He, ^{4}He and nuclear fragments up to ^{7}Li

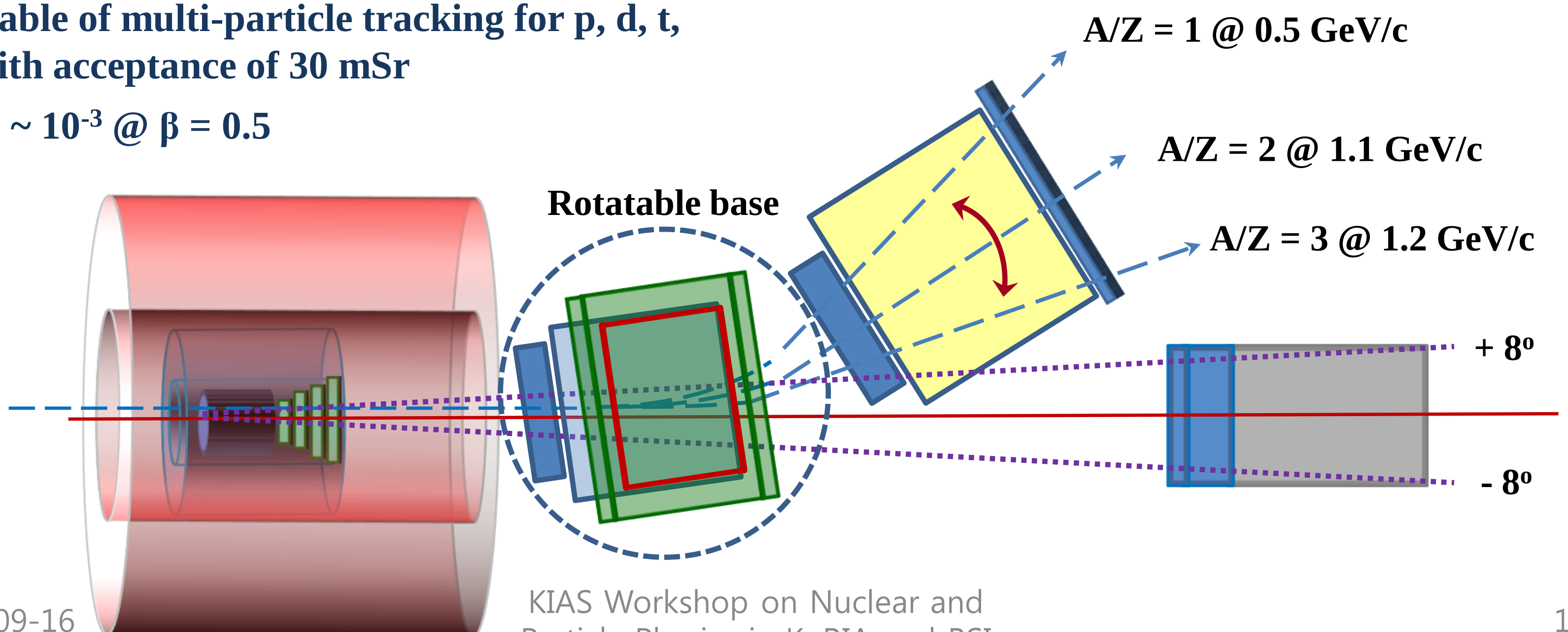
Silicon-strip trackers

- To measure hi-rapidity charged particles and nuclear fragments and reaction plane.

Dipole magnet & focal plane detectors

- Dipole magnet: 0.35 < p/Z < 1.5 GeV/c with max. ∫B∘dl = 1.5 Tm
- Capable of multi-particle tracking for p, d, t, α with acceptance of 30 mSr
- $\Delta p/p \sim 10^{-3}$ @ β = 0.5

- **Cylindrical TPC in the solenoid magnet:**
  TPC measures minimum-ionizing particles such as π^- and π^+ with presence of projectile-like residues and strong-ionizing fragments.
- **In the spectrometer arm(s)**
  TOF system with 100-ps time resolution: required to obtain $\Delta p/p \sim 10^{-3}$ @ β = 0.5
- **Neutron detector**
  Efficiency > 80%
  Capable of resolving multi-neutron events

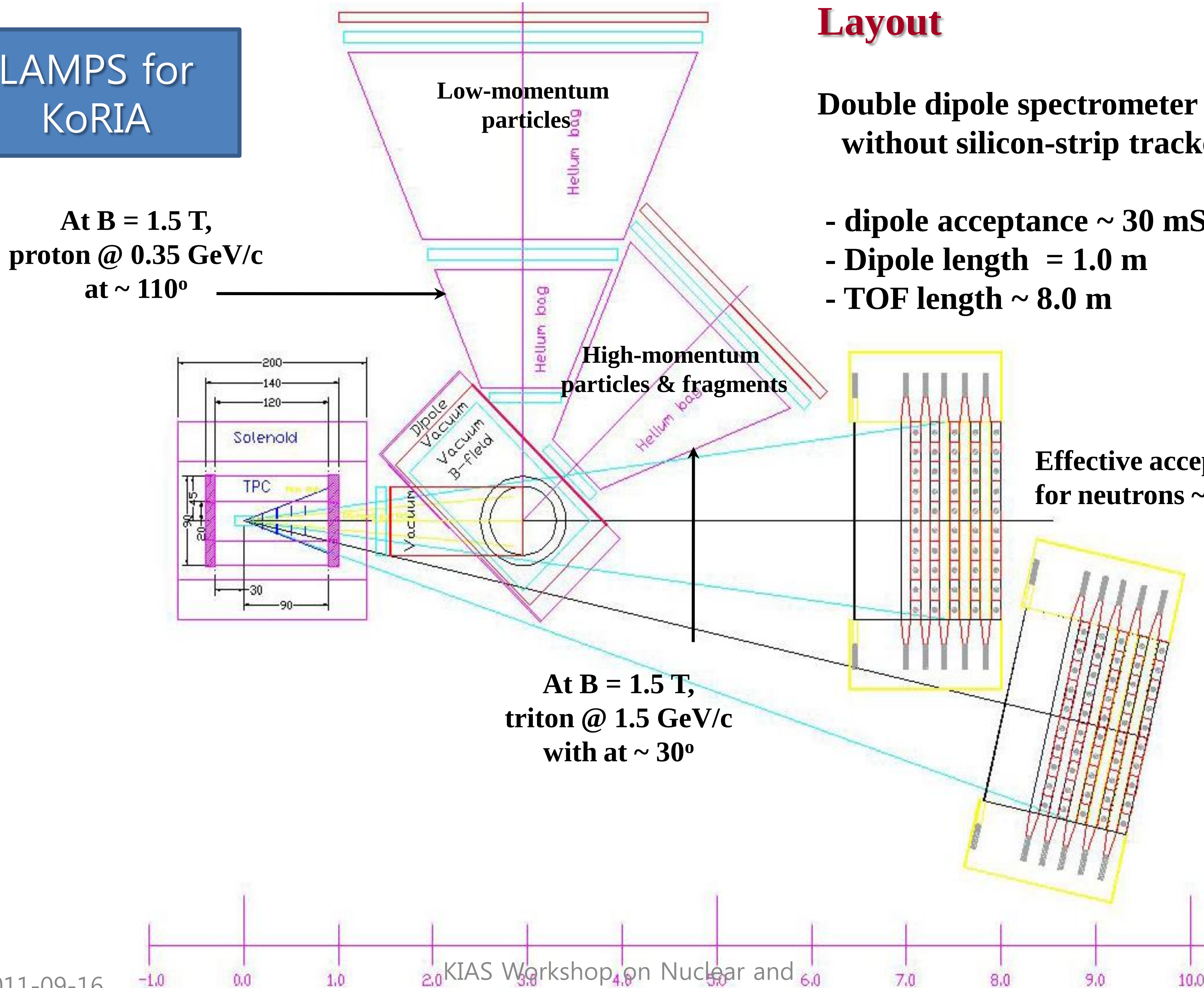


LAMPS for KoRIA

Layout

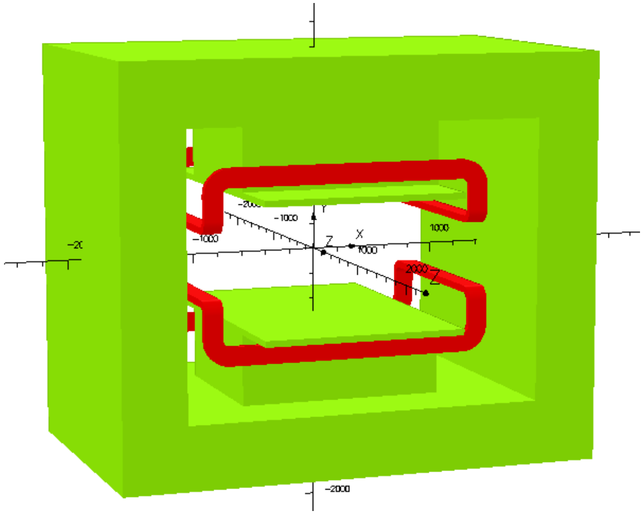
Double dipole spectrometer arms without silicon-strip trackers

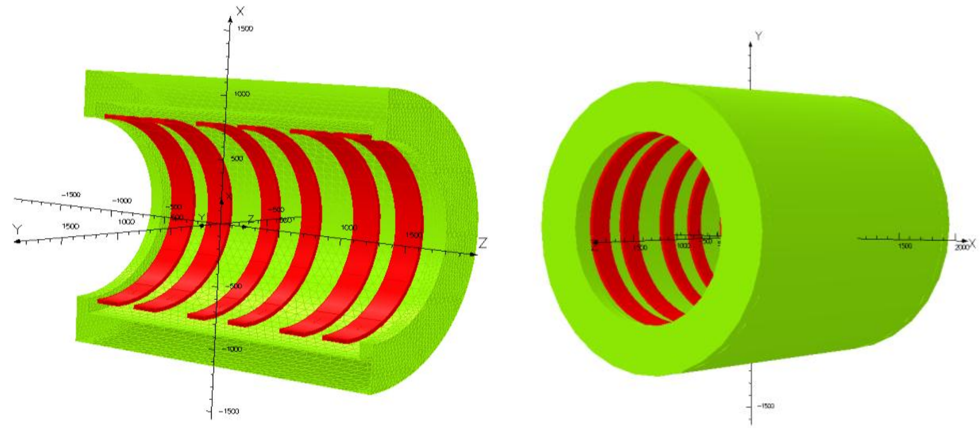
- **dipole acceptance ~ 30 mSr**
- **Dipole length = 1.0 m**
- **TOF length ~ 8.0 m**



Effective acceptance for neutrons ~ 50 mSr

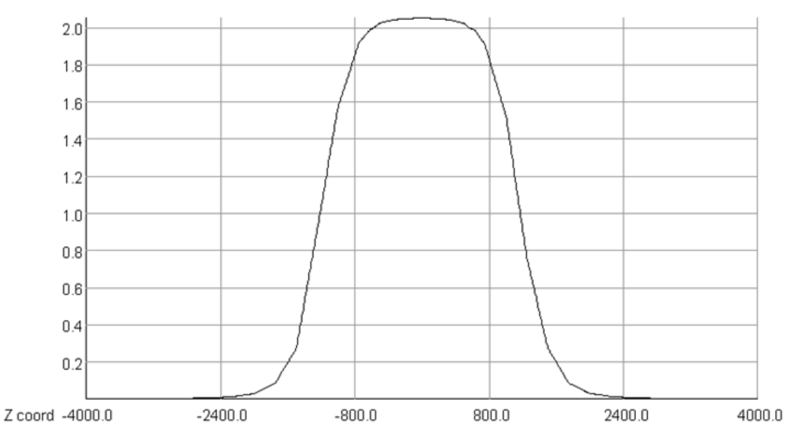
Solenoid and dipole magnets (TOSCA)

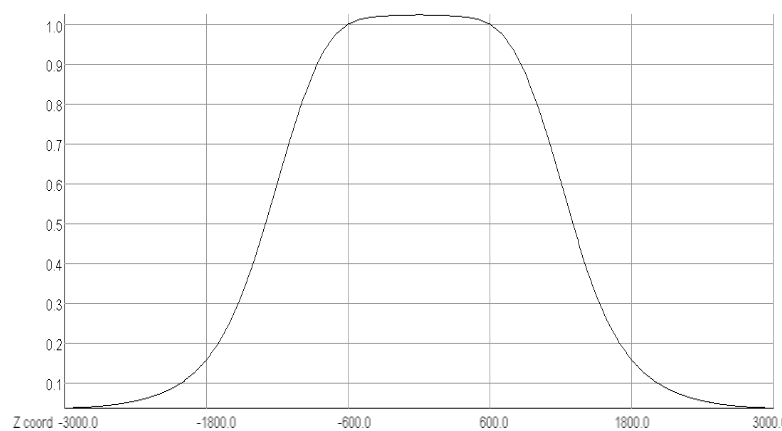




H-type Dipole
Pole size (x,z) : (150 cm, 100 cm)
Maximum B_y = 1.5 T
Gradient : 0.5 T·m < $\int B_y\, dz$ < 1.5 T·m

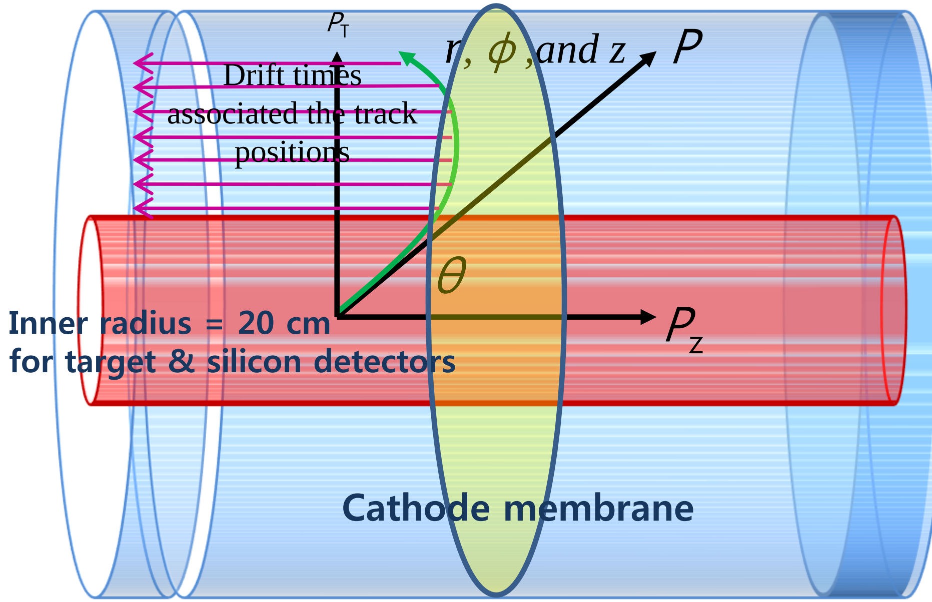
Solenoid
Size (r,z) : (50 cm, 200 cm)
Maximum B_z ~ 1.0 T



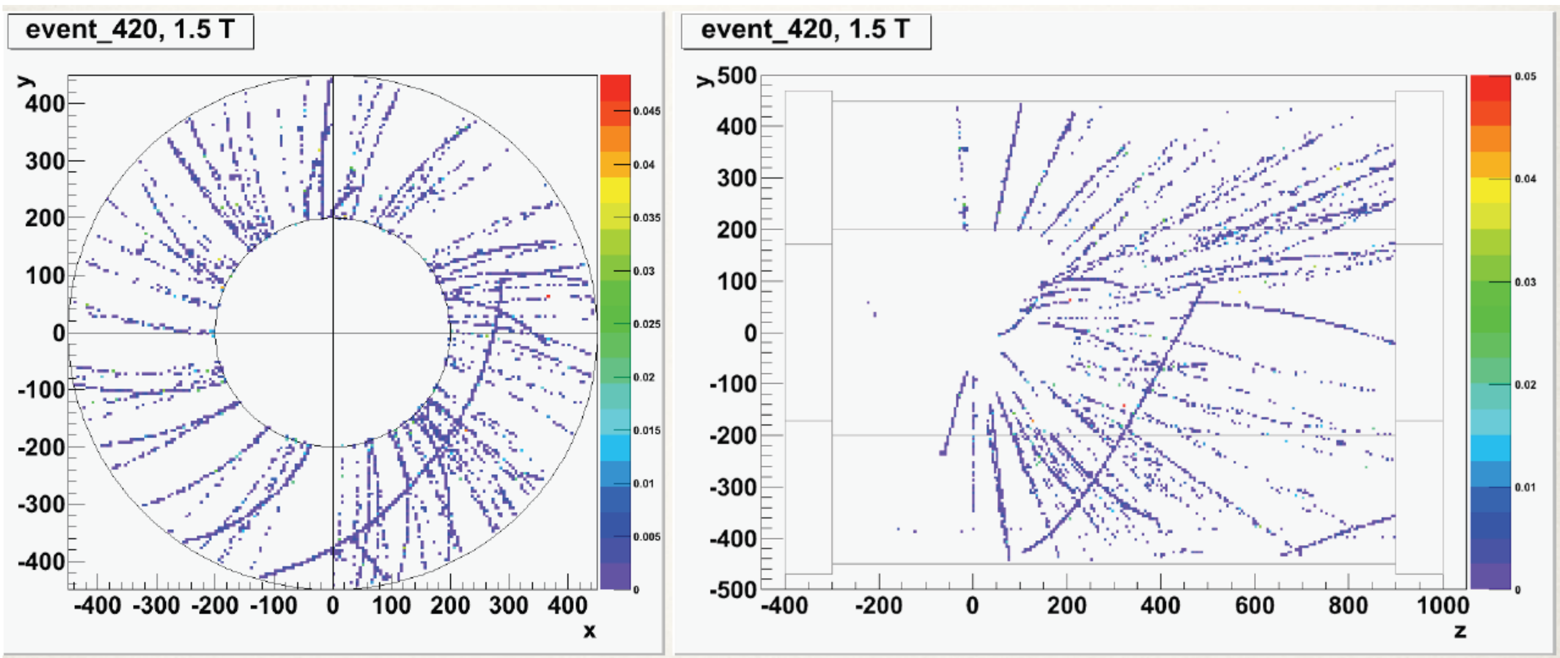


A cylindrical TPC

- 0.35< p/Z < 1.5 GeV/c
  for π, p, d, t, ^{3}He, ^{4}He
- Acceptance ~ 8 Sr
- A compact TPC with GEM readout
- OD: 90 cm, ID: 40 cm, L = 120 cm



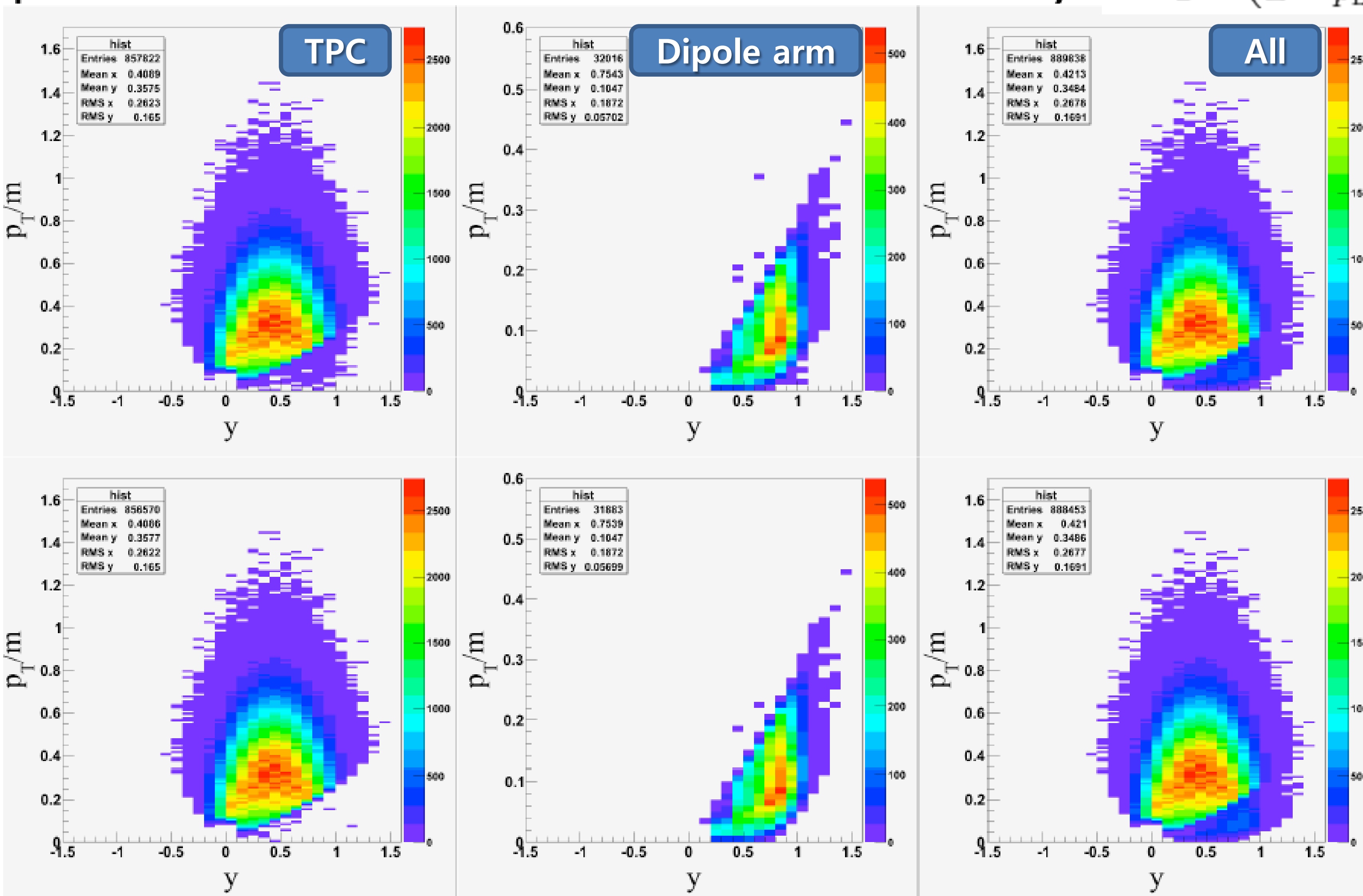
Simulated events for p (GEANT4)



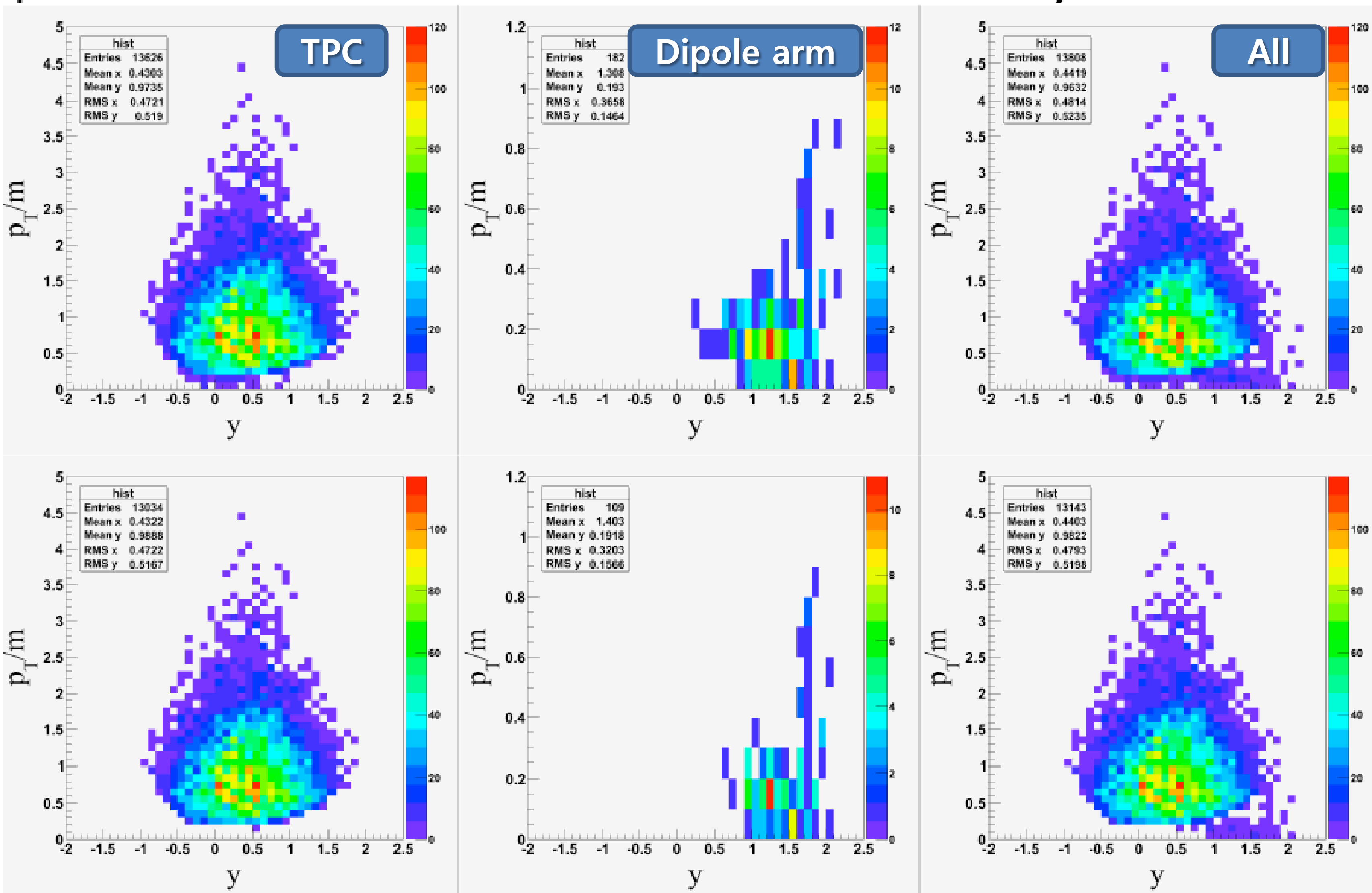
IQMD output + GEANT4

proton 400 MeV Soft Model w/ Secondary

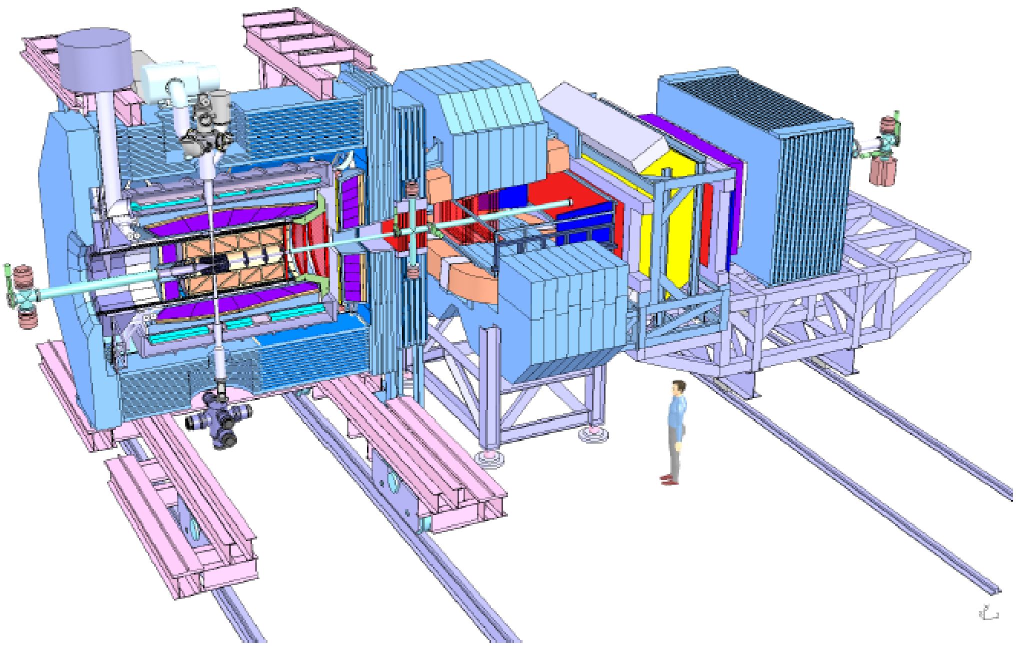
$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$



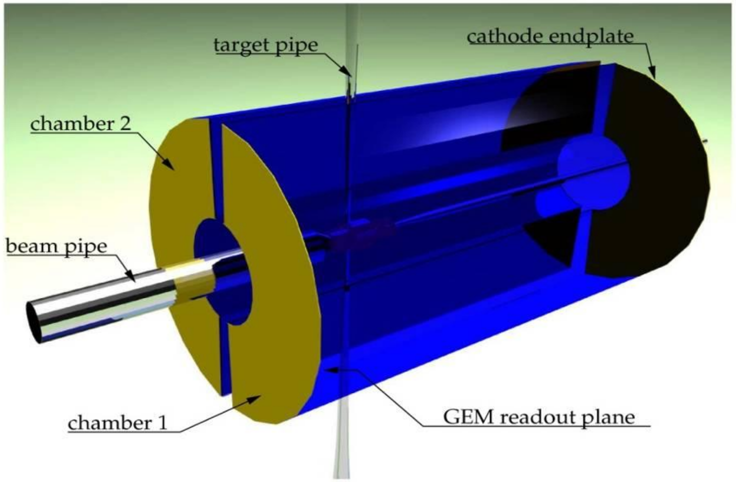
pi+ 400 MeV Soft Model w/ Secondary



PANDA for hadron spectroscopy, nuclear structure, & hypernuclei (FAIR, GSI)



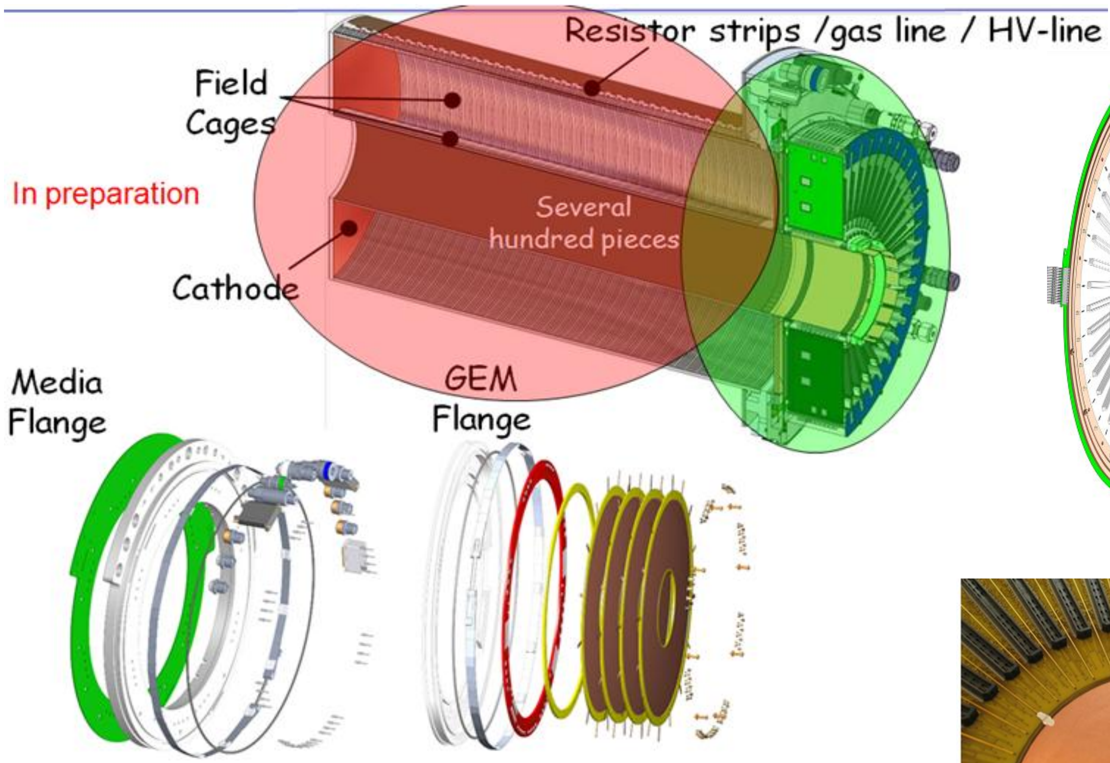
TPC central tracker



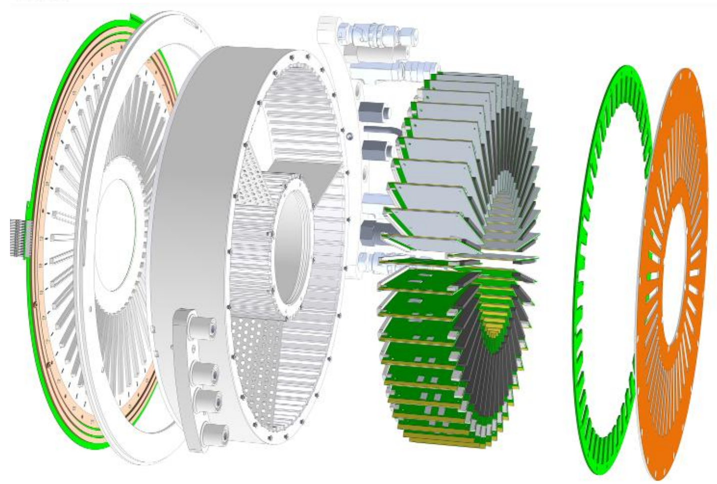
- NIMA 628 204 (2011)
- IEEE NSS Conf. Rec. N12-1 (2007)
- IEEE NSS Conf. Rec. N44-3 (2009)

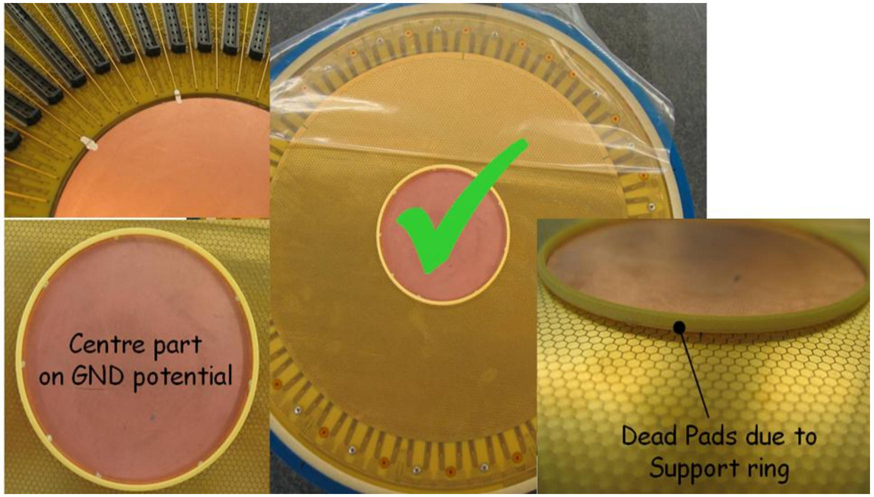
- 2 half cylinders L=150cm R=15/42cm
- Drift field 400 V/cm
- Ne/CO_2 (90/10), max. drift time 55μs
- Multi-GEM stack
- Pad Size ~2x2mm^2, 100.000 ch

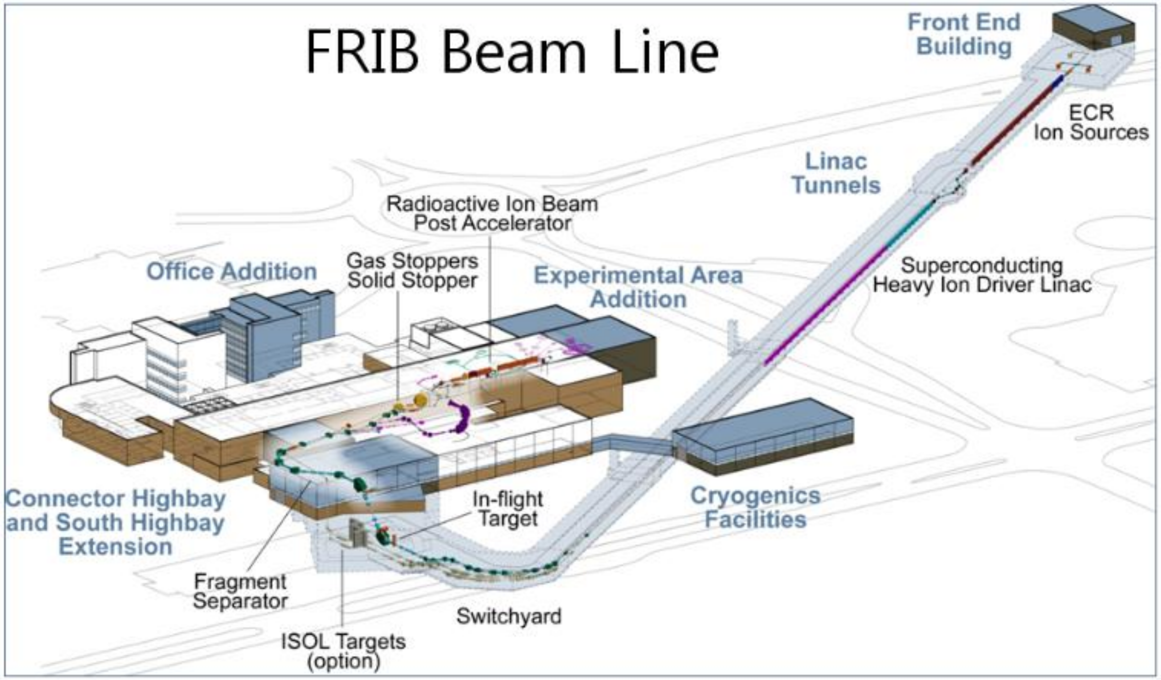
TPC at PANDA/GSI



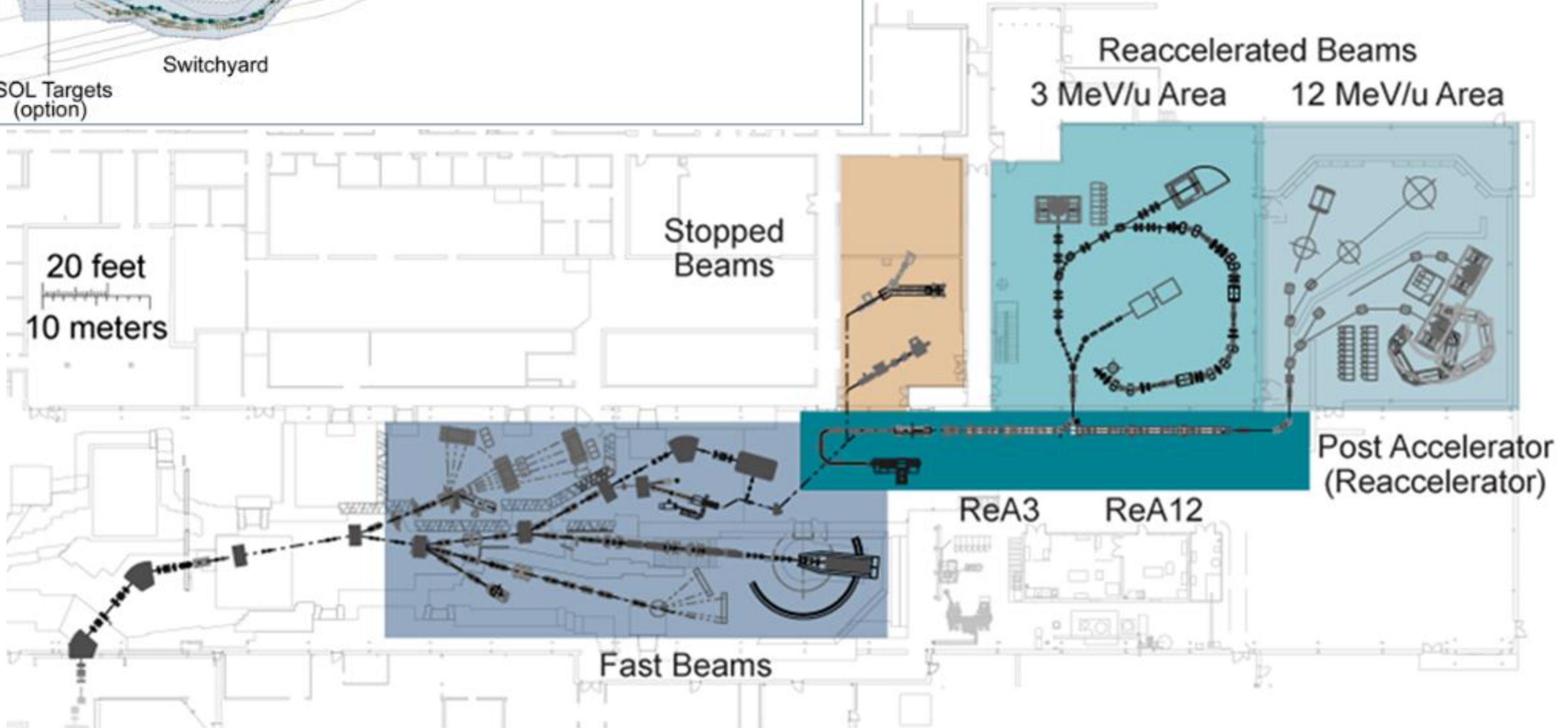
Electronics Flange



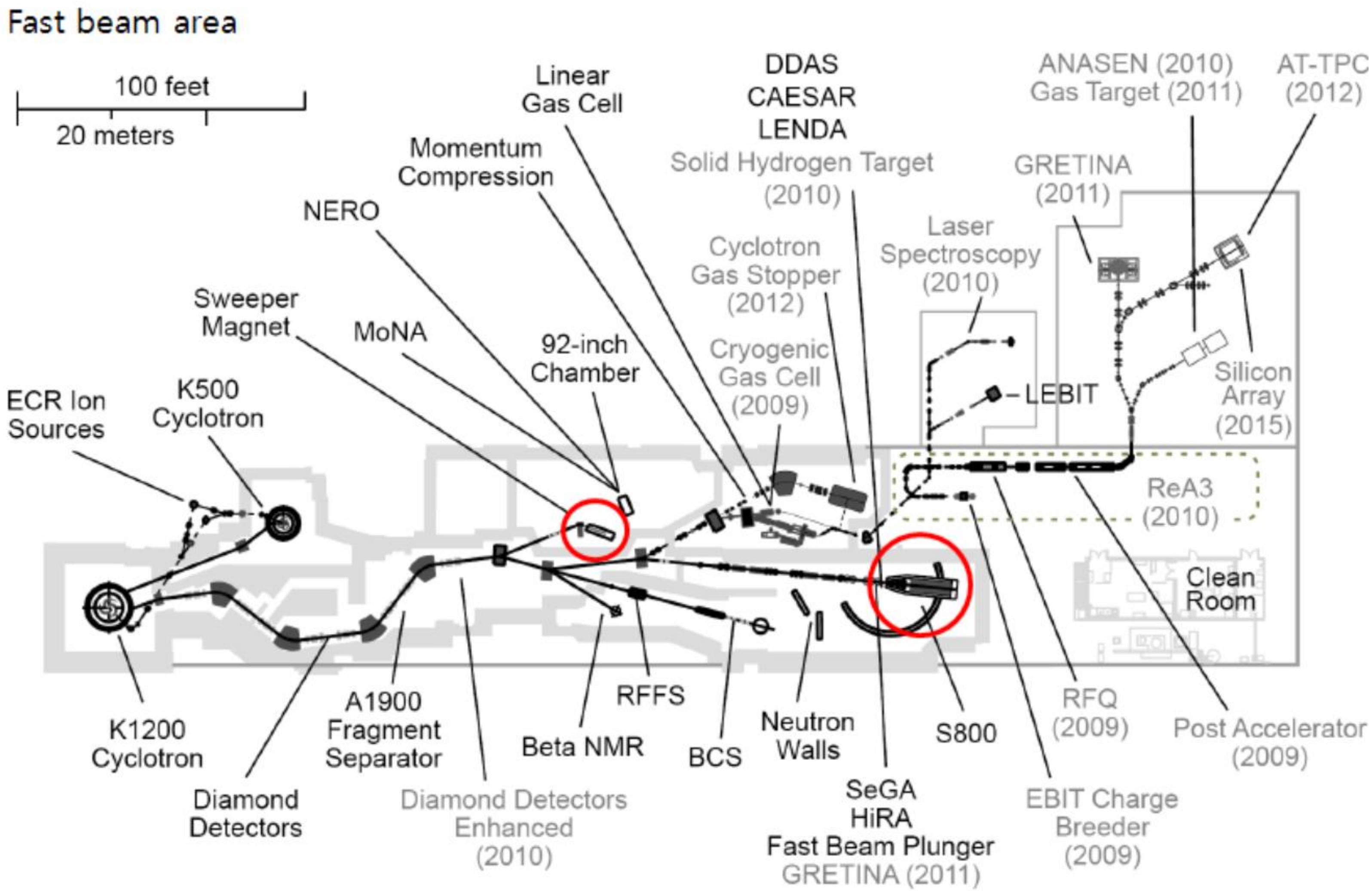



FRIB Beam Line
Front End Building
ECR Ion Sources
Linac Tunnels
Radioactive Ion Beam Post Accelerator
Gas Stoppers Solid Stopper
Office Addition
Experimental Area Addition
Superconducting Heavy Ion Driver Linac
Connector Highbay and South Highbay Extension
In-flight Target
Cryogenics Facilities
Fragment Separator
Switchyard
ISOL Targets (option)

FRIB

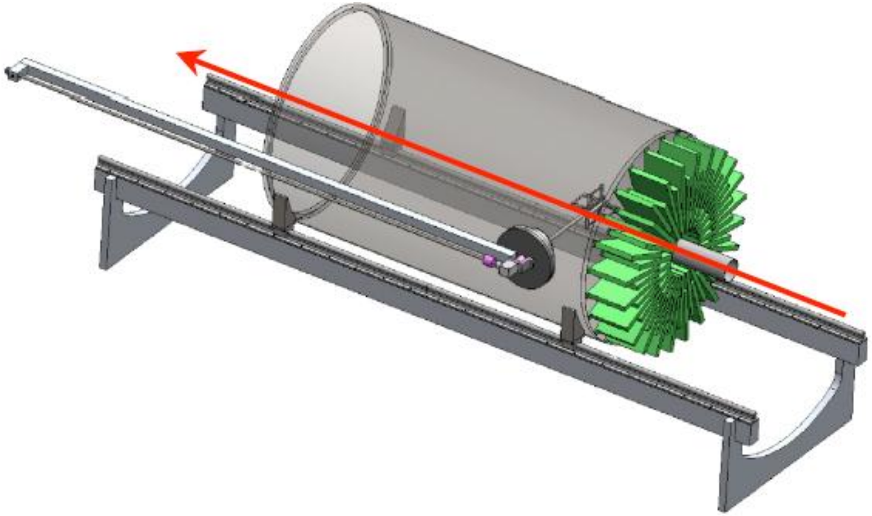

Reaccelerated Beams
3 MeV/u Area
12 MeV/u Area
Stopped Beams
20 feet
10 meters
Post Accelerator (Reaccelerator)
ReA3
ReA12
Fast Beams

FRIB



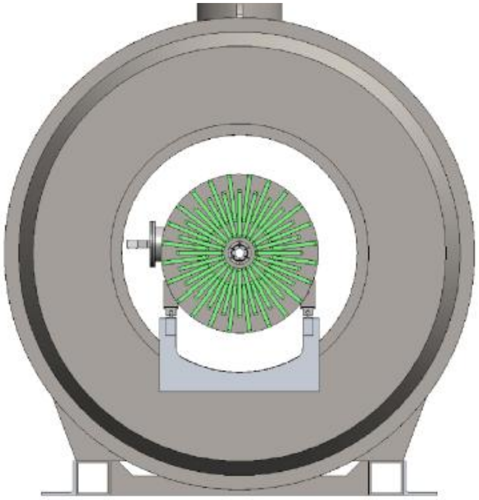
Fast beam area
100 feet
20 meters
Linear Gas Cell
DDAS
CAESAR
LENDA
Solid Hydrogen Target (2010)
ANASEN (2010)
Gas Target (2011)
AT-TPC (2012)
GRETINA (2011)
Momentum Compression
NERO
Cyclotron Gas Stopper (2012)
Laser Spectroscopy (2010)
Sweeper Magnet
MoNA
92-inch Chamber
Cryogenic Gas Cell (2009)
LEBIT
Silicon Array (2015)
ECR Ion Sources
K500 Cyclotron
ReA3 (2010)
Clean Room
K1200 Cyclotron
A1900 Fragment Separator
RFFS
Neutron Walls
S800
RFQ (2009)
Post Accelerator (2009)
Beta NMR
BCS
Diamond Detectors
Diamond Detectors Enhanced (2010)
SeGA
HiRA
Fast Beam Plunger
GRETINA (2011)
EBIT Charge Breeder (2009)

Active Target TPC FRIB



NSCL: AT-TPC

- Cylinder - length 120cm, radius 35cm
- Chamber designed to sustain vacuum
- 2cm radius entrance window
- 33cm radius exit window
- Removable target wheel
- 10,000pads, 0.5cm x 0.5cm
- Testing wire planes, GEMS & Micromegas for electron amplification



- Superconducting solenoid
- 2 Tesla Field
- Bore Dimensions:
  - ≥ 70 cm diameter
  - ≥ 120 cm length
  - ≤ 125 cm beam height
- Field Non-uniformity: ≤ 10%

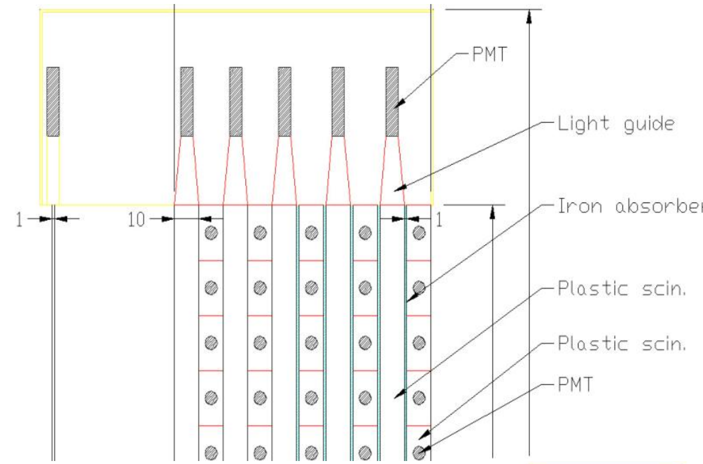
Neutron detector Array

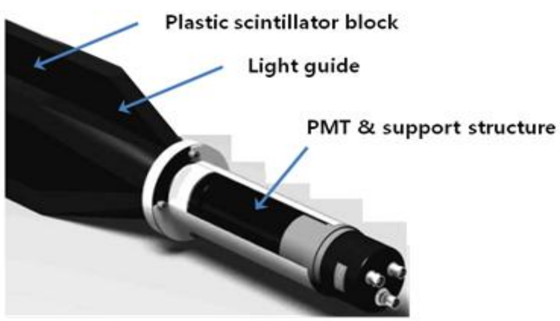
- Veto counter array
- Plastic scintillator array
- ~~Sampling calorimeter array~~

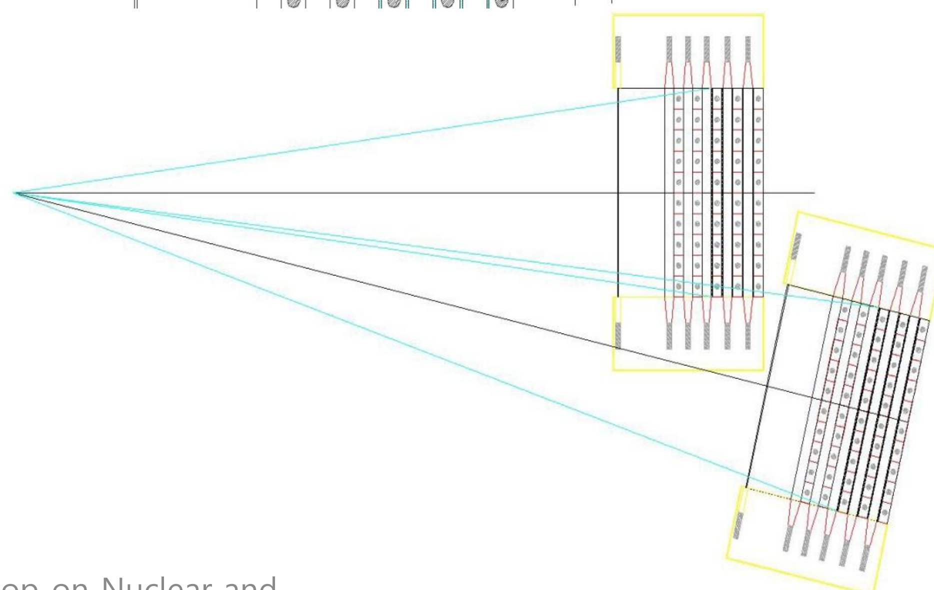
- Time resolution ~ 1 ns to measure TOF for energy determination
- Capable of multi-hit by analysis of hit pattern

- Efficiency > 80% for 30 MeV < E_n < 300 MeV

- TOF measurements → determination of energy
  $\Delta E/E$ < 0.03 for E_n < 50 MeV,
  $\Delta E/E$ ~ 0.05 for E_n > 50 MeV
- 1-cm thick veto counter array to veto charged particles

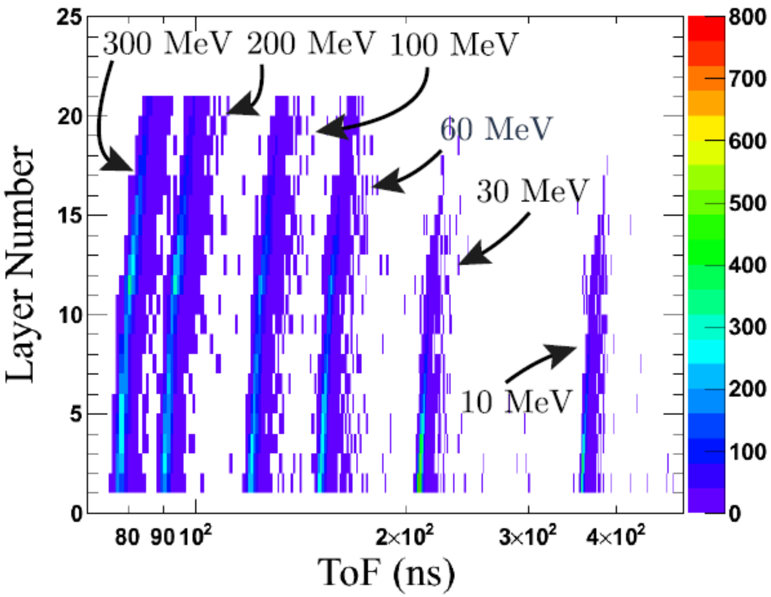


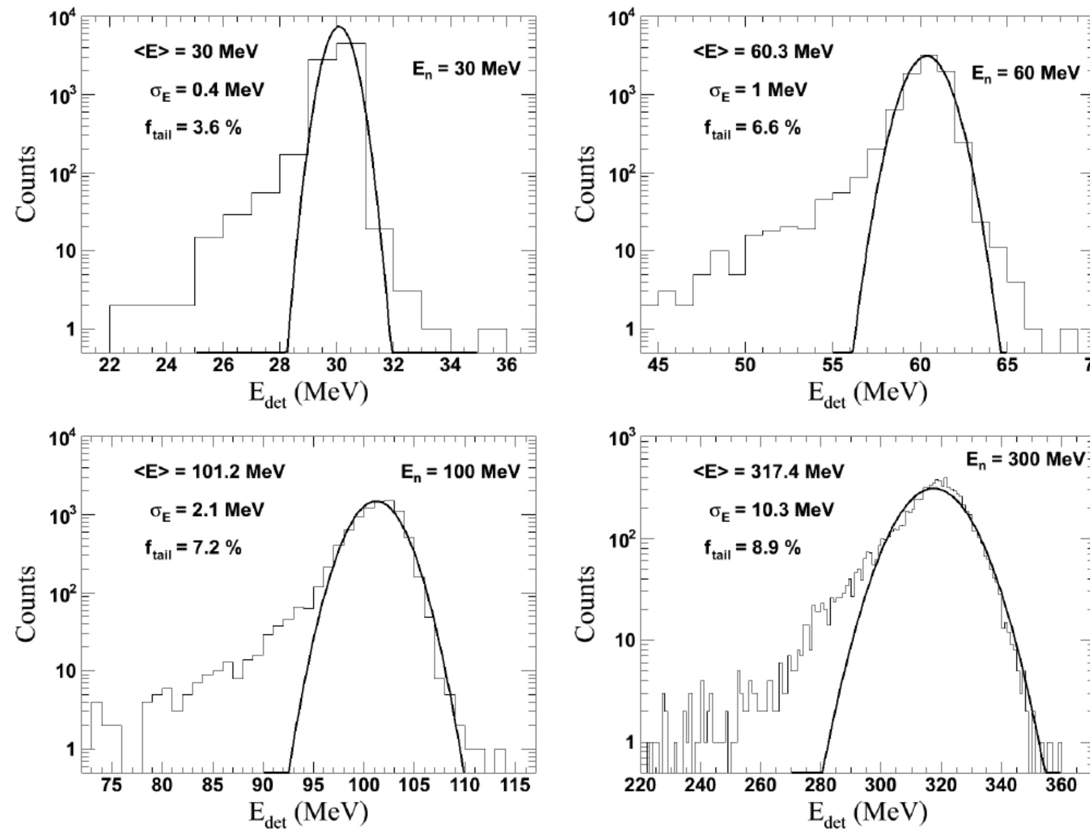




Determination of the neutron energy by measuring TOF of the first hit

- Time resolution of the plastic detector module ~ 1 ns
- TOF length = 15 m (distance from the target to the neutron detector)





4. Current Status & Discussions

1. GEANT4 Simulation for the LAMPS system for a full reconstruction of simulation data for LAMPS
   - Cylindrical TPC in a solenoid magnet (1 T)
   - Neutron detector array
   - Ray tracing in a dipole magnet (upto 1.5 T)
     need detailed B field mapping by using TOSCA simulations
   - Focal plane detectors (DC & TOF array) in dipole arms

2. Planning to test a unit detector for the neutron detector array
   - Purchased plastic scintillators ($10 \times 10 \times 100$ cm^3) & PMTs
   - DAQs: VME (FADC) + CAMAC (ADC + TDC)
   - ^{252}Cf source: TOF measurement for neutron with energy up to 7 MeV

3. Detailed design for the dipole magnet & the focal plane detectors

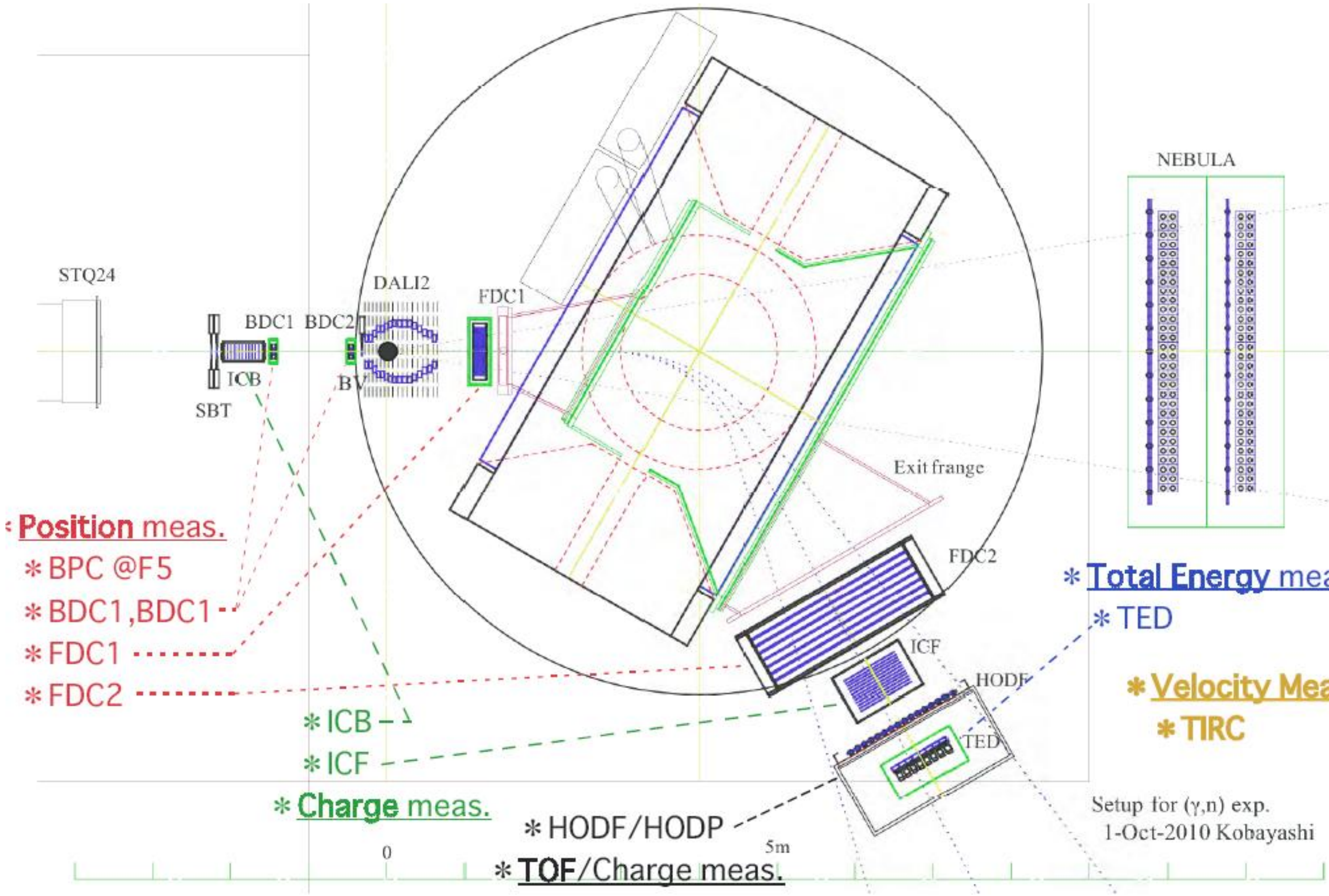
- Decision of physics with available RI by IFF & ISOL in KoRIA
- Stable beams: p(polarized or non-polarized), Ar, U, Xe, Kr …
- Then, an optimal specification with the required rigidity

4. For precision measurements of nuclear fragmentations

- B > 2T to obtain a field integral $\int B\,dz > 4$ Tm

  → **Super conducting dipole magnet**
- Required momentum resolving power ~ a few thousands
- Need dedicated detector system minimizing energy loss for the heavy particles in narrow kinematical ranges.

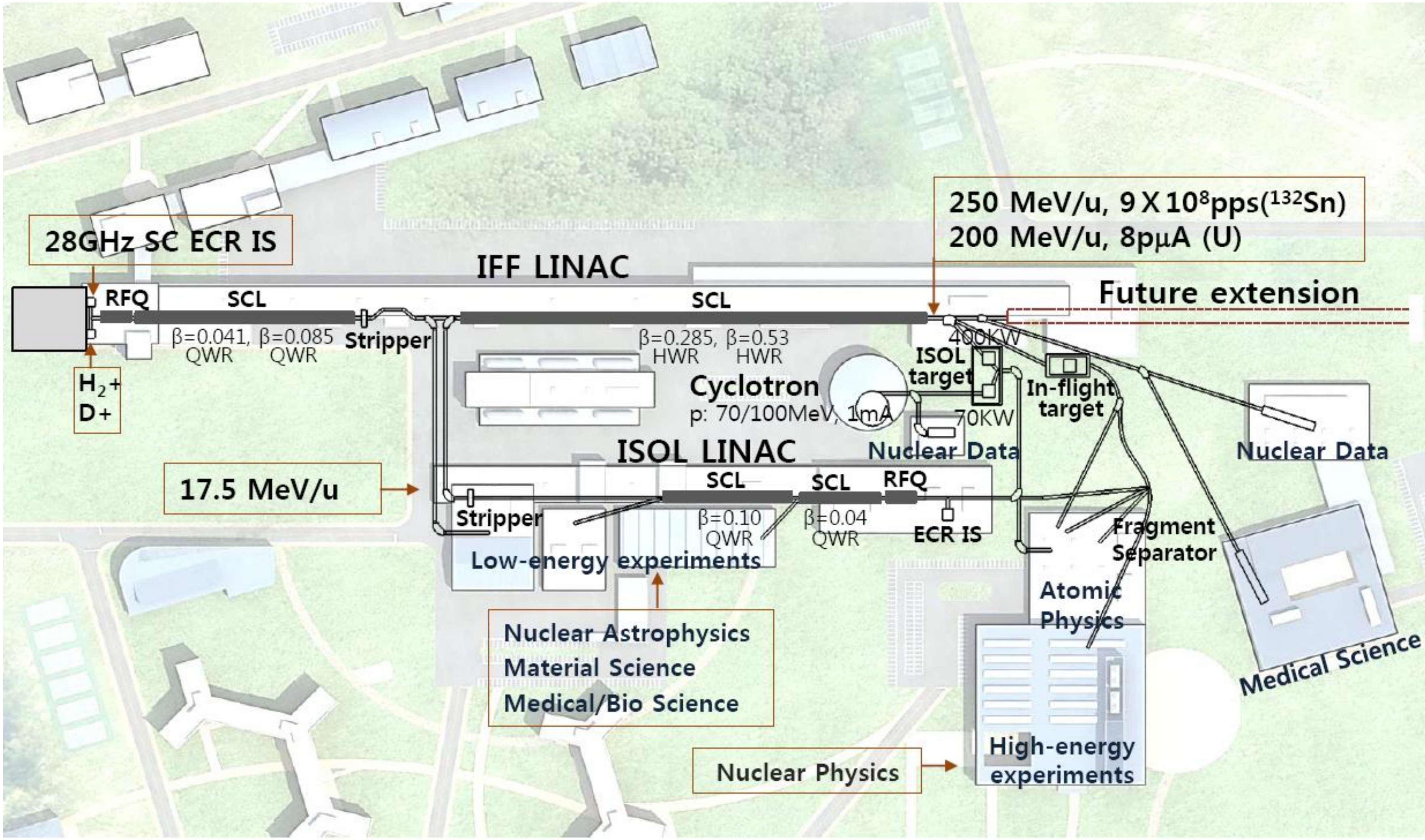
5. Gamma-ray detectors before surrounding the target


STQ24
SBT
BDC1
BDC2
ICB
BV
DALI2
FDC1
NEBULA
Exit frange
FDC2
ICF
HODF
TED
Position meas.
* BPC @F5
* BDC1,BDC1
* FDC1
* FDC2
* ICB
* ICF
* Charge meas.
* HODF/HODP
* TOF/Charge meas.
* Total Energy meas.
* TED
* Velocity Meas.
* TIRC
0
5m
Setup for (γ,n) exp.
1-Oct-2010 Kobayashi

BACK UPS

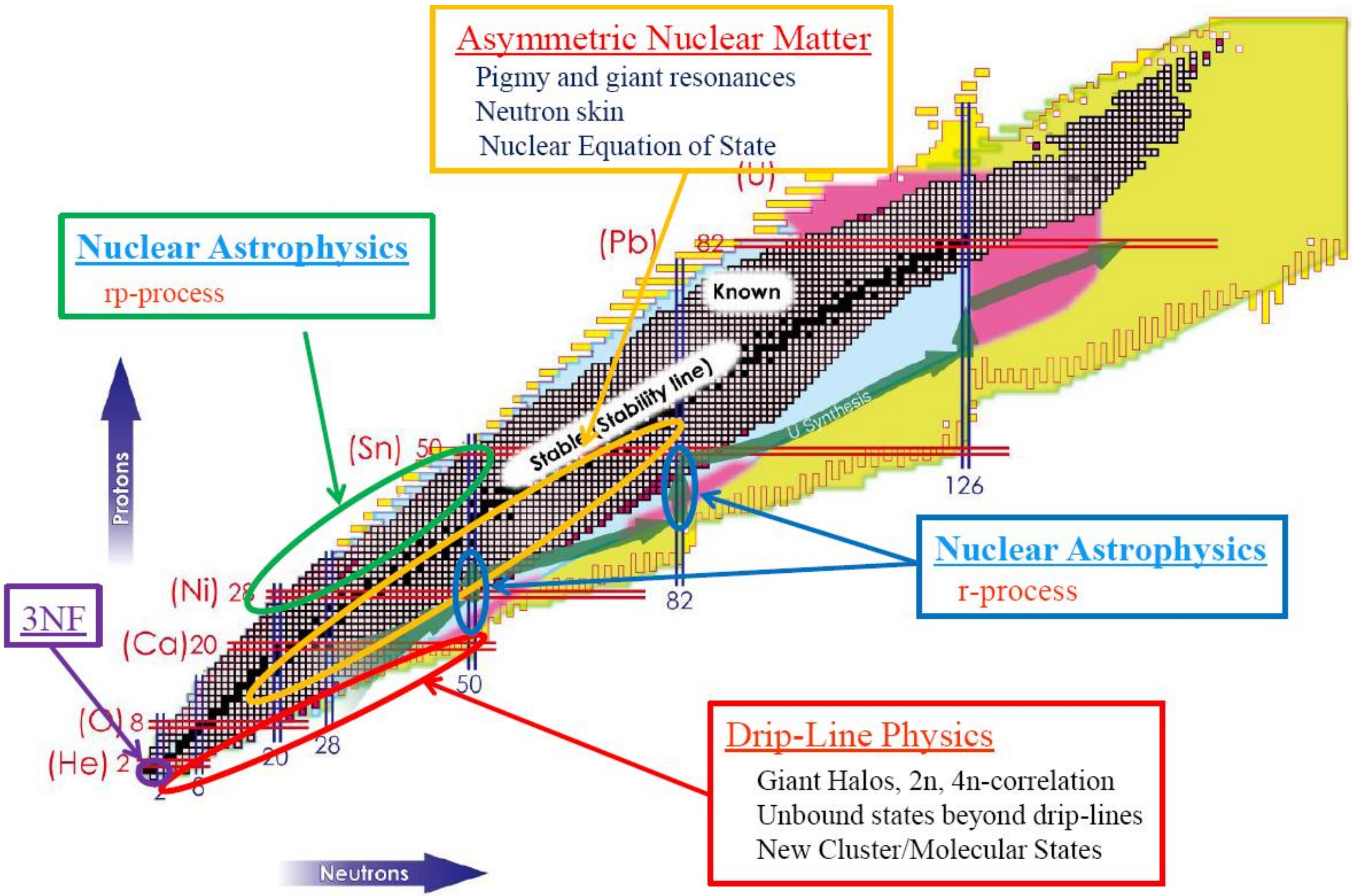
1. Introductions

Korea Rare Isotope Accelerator Facility



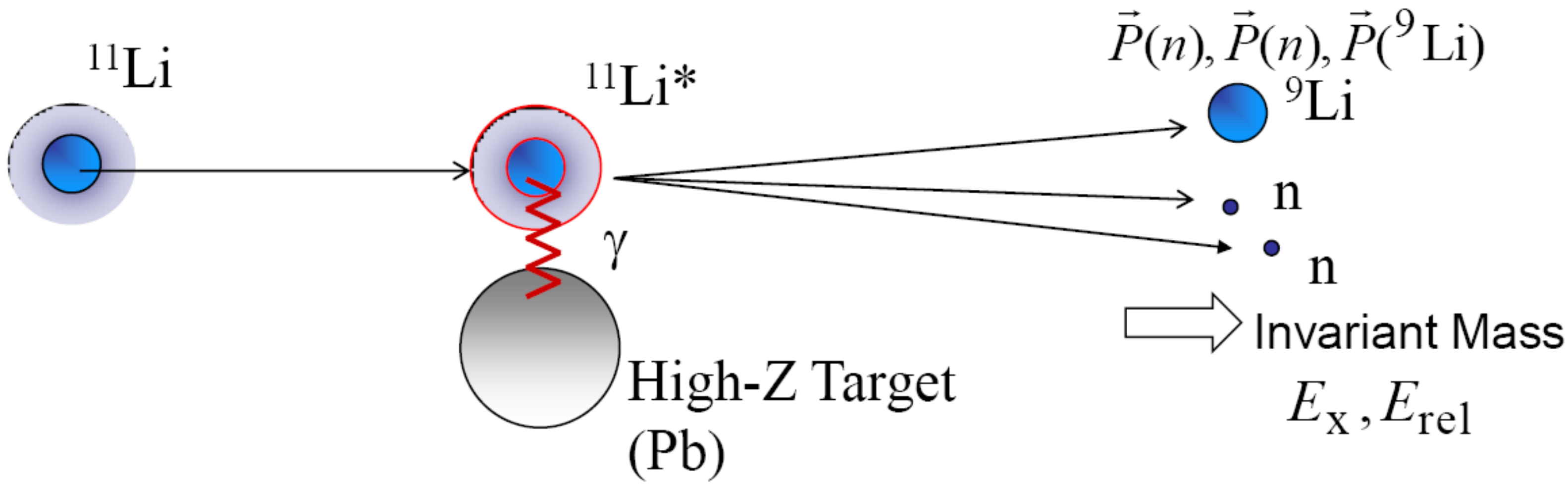
KoRIA RI Beam intensities compared for ISOL & IFF

RIB species	ISOL (pps)	In-Flight Fragmentation (pps)	comment
^{15}O	$5x10^8$ * $^{19}F(p,\alpha n)$, LiF pressed powder	To be estimated	Nuclear astropysics
^{94}Kr	$4x10^9$	$4x10^2$	Nuclear structure
^{109}Y	$2x10^5$	$<10^2$	New discovery at RIKEN
^{117}Mo	Not available due to low vapor pressure	$<10^3$	New discovery at RIKEN
^{132}Sn	$9x10^8$	$2x10^5$	Double magic
^{142}Xe	$1x10^{10}$	$1x10^4$	Symmetry energy
^{144}Cs	$7x10^8$	$3x10^4$	Nuclear astrophysics



Asymmetric Nuclear Matter
Pigmy and giant resonances
Neutron skin
Nuclear Equation of State
Nuclear Astrophysics
rp-process
Nuclear Astrophysics
r-process
Drip-Line Physics
Giant Halos, 2n, 4n-correlation
Unbound states beyond drip-lines
New Cluster/Molecular States
3NF
Protons
Neutrons
Known
Stable (Stability line)
U Synthesis
(U)
(Pb) 82
(Sn) 50
(Ni) 28
(Ca) 20
(O) 8
(He) 2
2
8
20
28
50
82
126

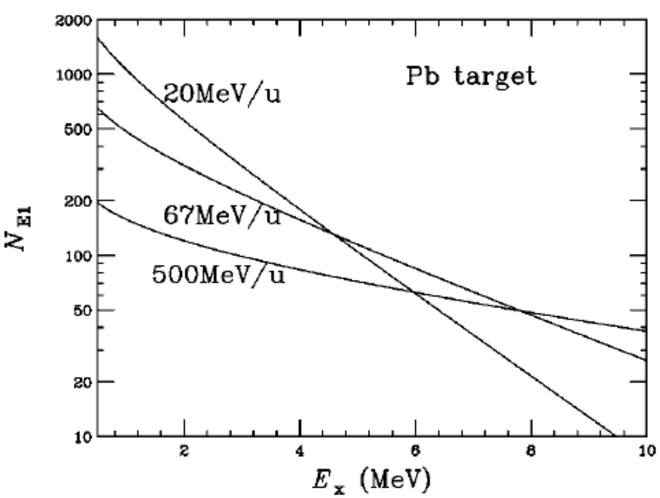
Coulomb Breakup



Equivalent Photon Method

$$\frac{d\sigma(E1)}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

Cross section = (Photon Number)x(Transition Probability)

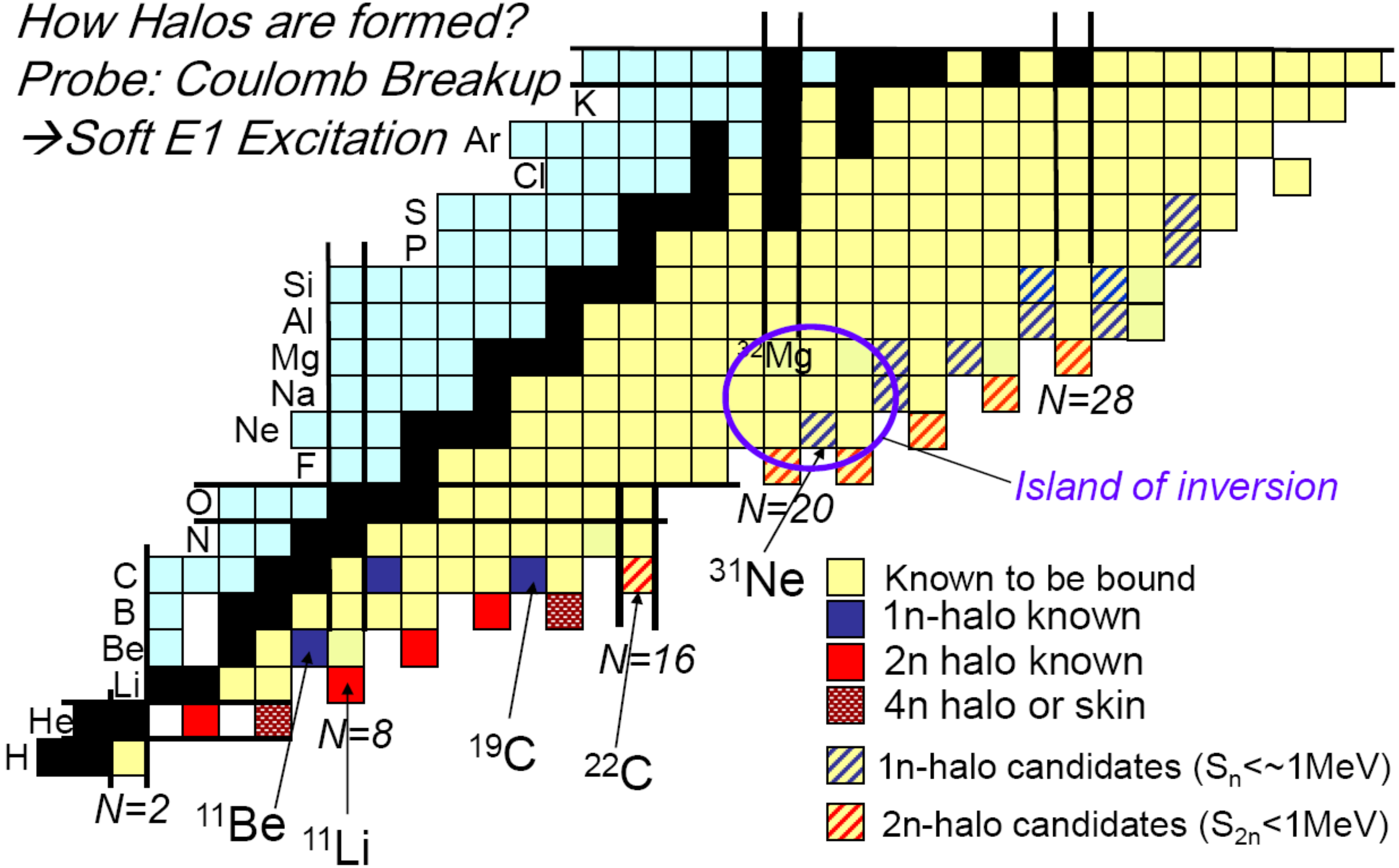


How neutron-drip line looks like towards heavier nuclei?

How Halos are formed?

Probe: Coulomb Breakup

→Soft E1 Excitation



N.B. S_n,S_{2n}: Estimated value by Audi & Wapstra (Jurado et al.(PLB649,43(2007)), incorporated)

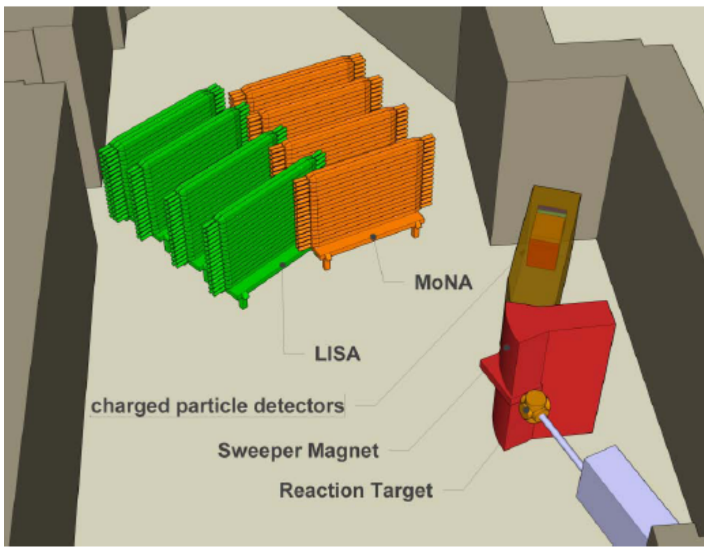
MoNA-LISA @ FRIB

<u>Physics motivation</u>

Structure of exotic neutron-rich nuclei along the neutron drip line.

Reconstruction of neutron unbound states from decay products:

fast neutron + fragment (+ γ)



MoNA-LISA

- MoNA : 144 individual plastic scintillator modules; 10 cm×10 cm×200 cm; stack to match experimental needs
- LISA: additional 144 modules (MRI – funded)

- <u>FRIB requirements for MoNA</u>: Flight path of at least 10 m to maintain the same energy resolution

<u>New HRS requirements – 7 Tm</u>

Acceptances similar to Sweeper

Larger flight path

Larger neutron window that extends to the side

A. Spyrou

MoNA-LISA @ FRIB

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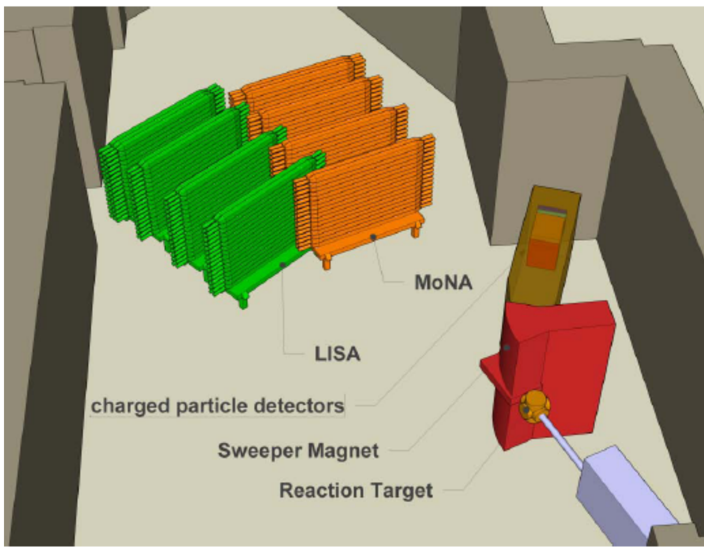

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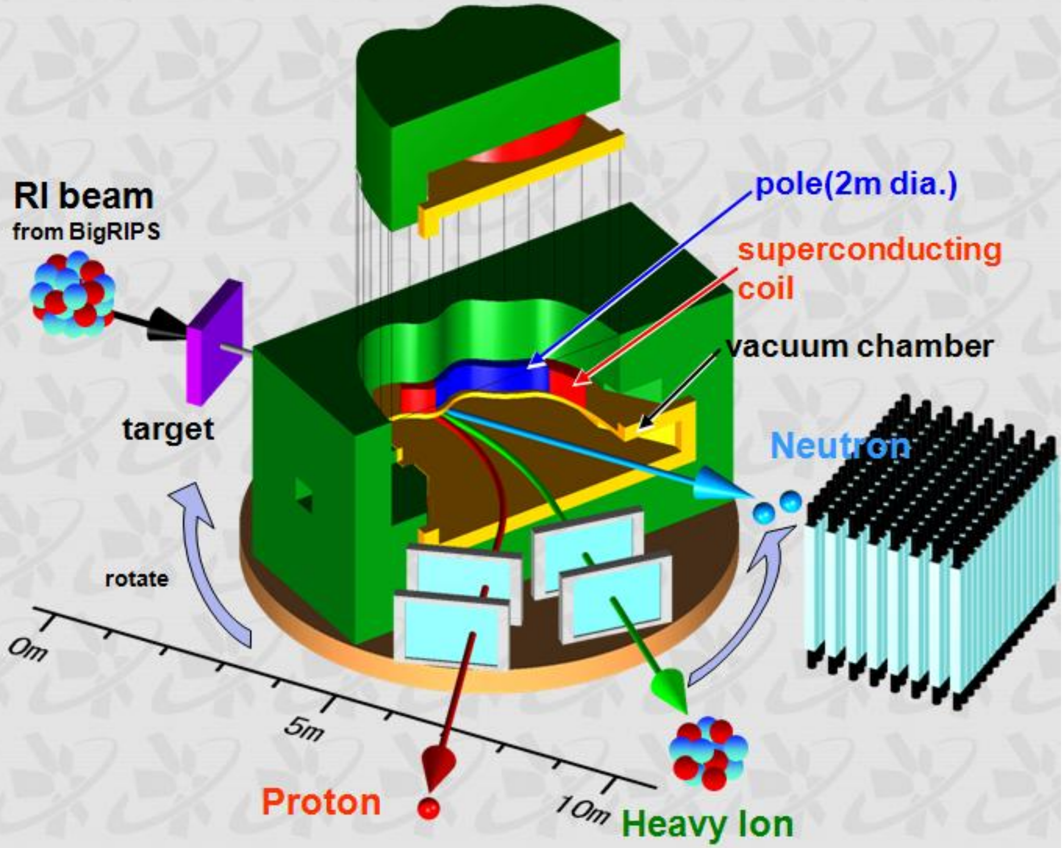
A. Spyrou

Outline of "SAMURAI"

SAMURAI spectrometer is designed for kinematically complete measurements by detecting multiple particles in coincidence.

SAMURAI consists of …

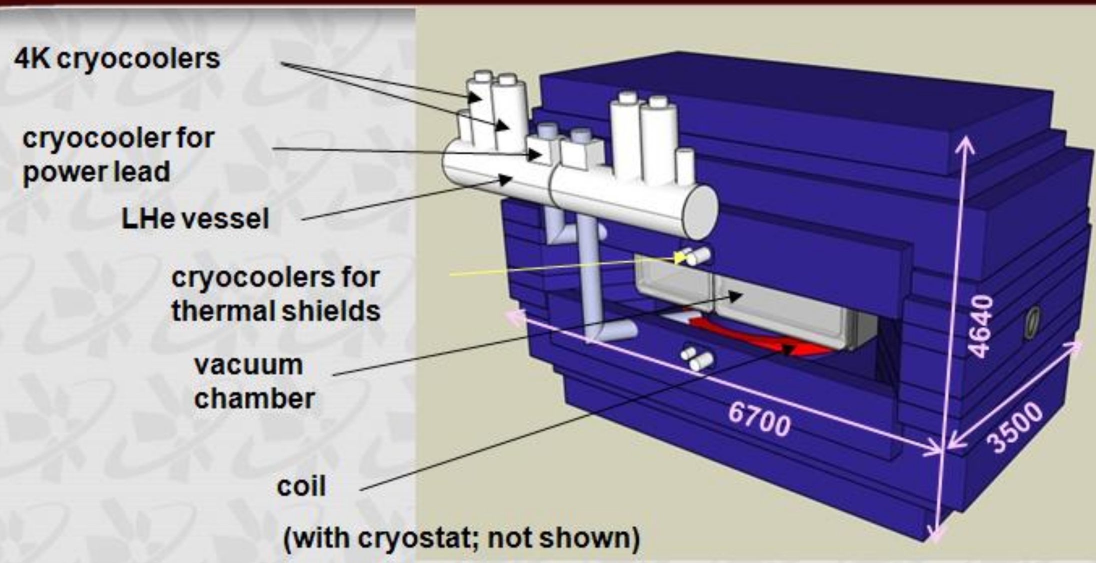
- ✓Superconducting magnet
- ✓Heavy Ion detectors
- ✓Proton detectors
- ✓Neutron detectors
- ✓Large vacuum chamber
- ✓Rotatable base

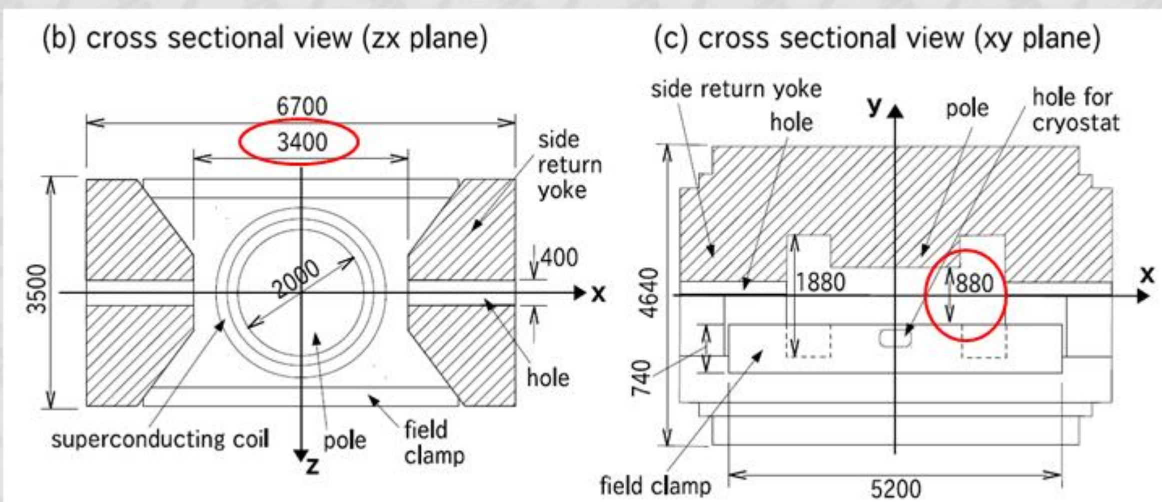


Geometry

Weight: ~600 ton

- yoke: 567 ton
- coil with cryostat: 8x2 ton
- vacuum chamber: 14 ton





Specification

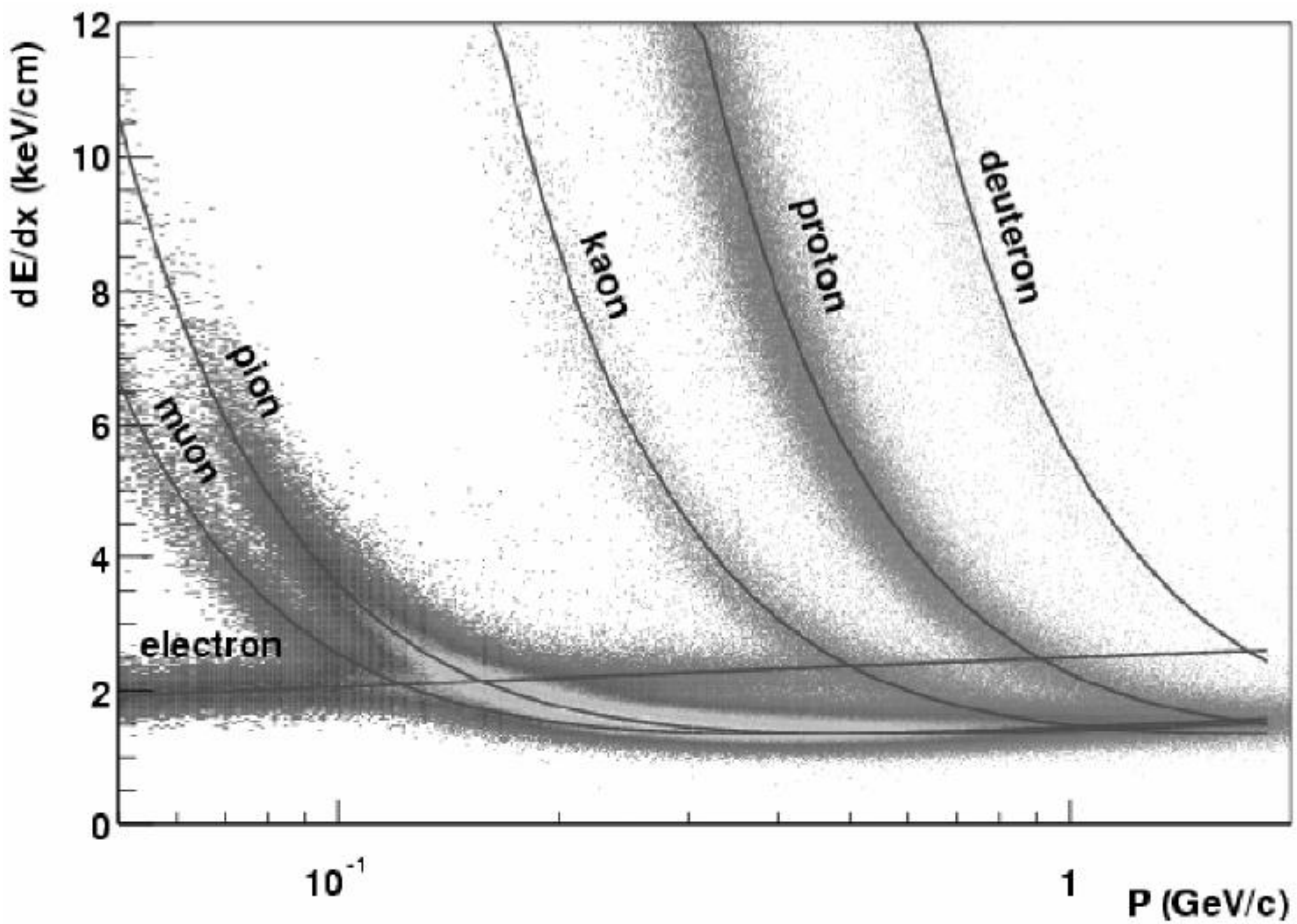
Table 1. Parameters of the superconducting dipole magnet.

	value
type	H-type, superconducting
number of turns	3411 turns/coil
current	560 A
magnetomotive force	1.9 MAT/coil
current density of coil	66.0 A/mm^2
field at the pole center (median plane)	3.1 T
BL integral at 3.1 T	7.05 Tm
maximum magnetic field in a coil	5.26 T
inductance	212 H
stored energy	33 MJ
coil inner diameter	2350 mm
outer diameter	2710 mm
cross section	180×160 mm^2
weight	1783 kg/coil
pole shape	circular
gap	880 mm
diameter	2000 mm
height	500 mm
yoke width	6700 mm
depth	3500 mm
height	4640 mm
weight	566140 kg

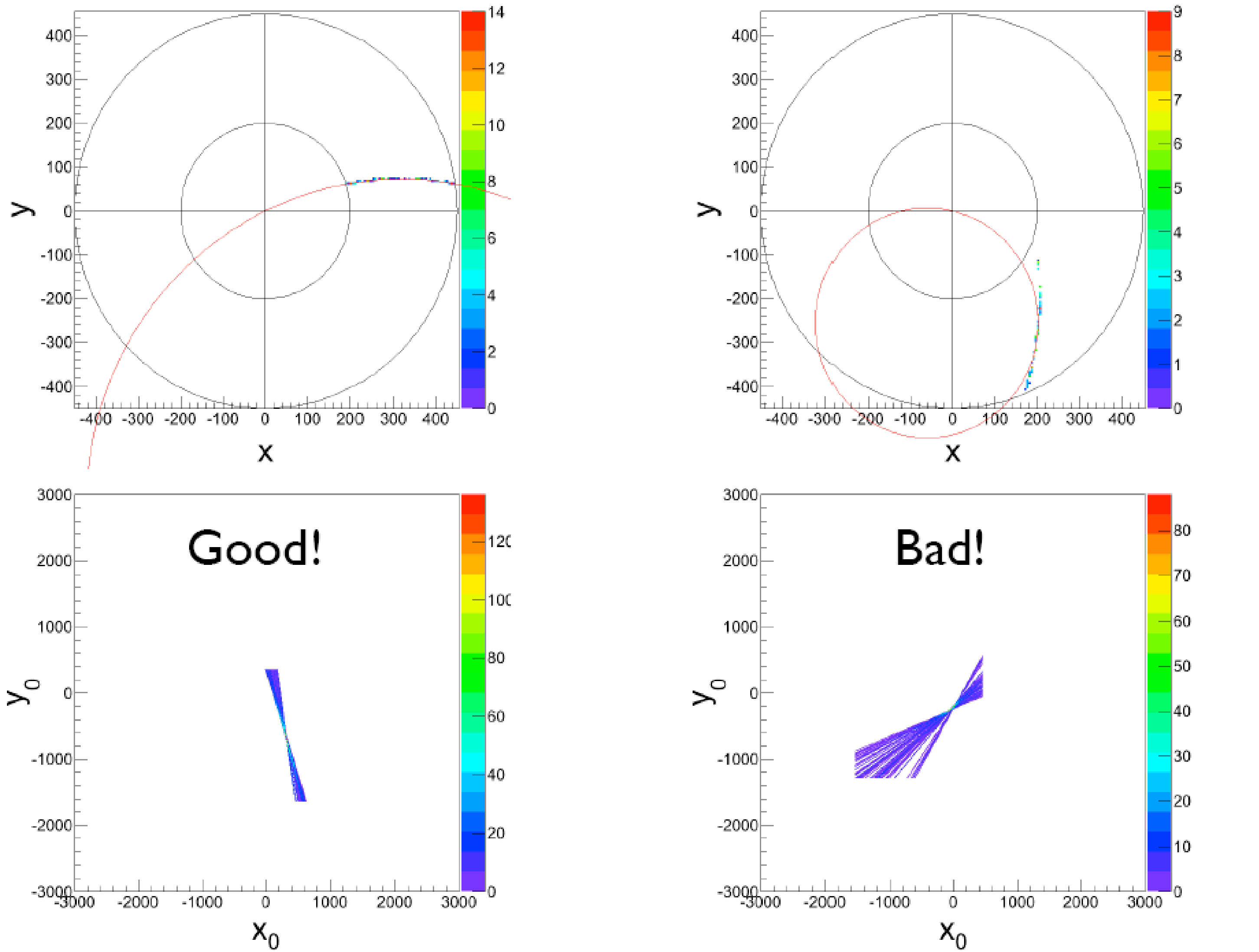
Table 2. Parameters of the superconducting wire.

	value
material	NbTi/Cu
diameter	3 mmϕ
Cu/SC ratio	5.0 $\sim$ 6.0
insulation	PVF($\geq$ 40 μm)
filament diameter	$\sim$28 μmϕ
number of filaments	$\sim$1760
twist pitch	$\sim$88 mm
RRR	$\geq$100
critical current at 4.2 K	$>$ 4000 A at 3 T $>$ 3290 A at 4 T $>$ 2690 A at 5 T $>$ 2150 A at 6 T

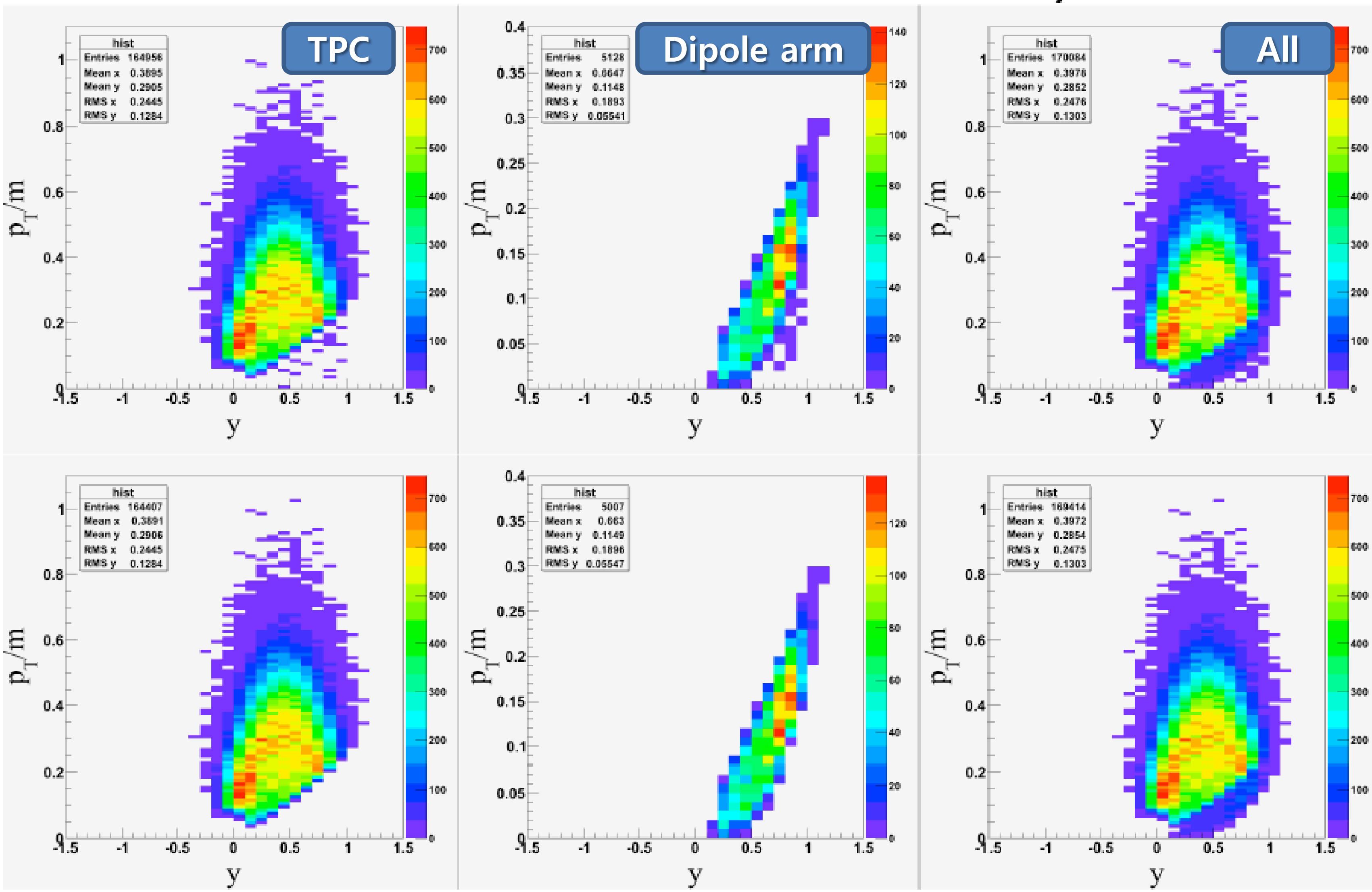
The energy loss distribution for primary and seconday particles in the STAR TPC as a function of the p_T of the primary particle. The magnetic field was 0.25 T.



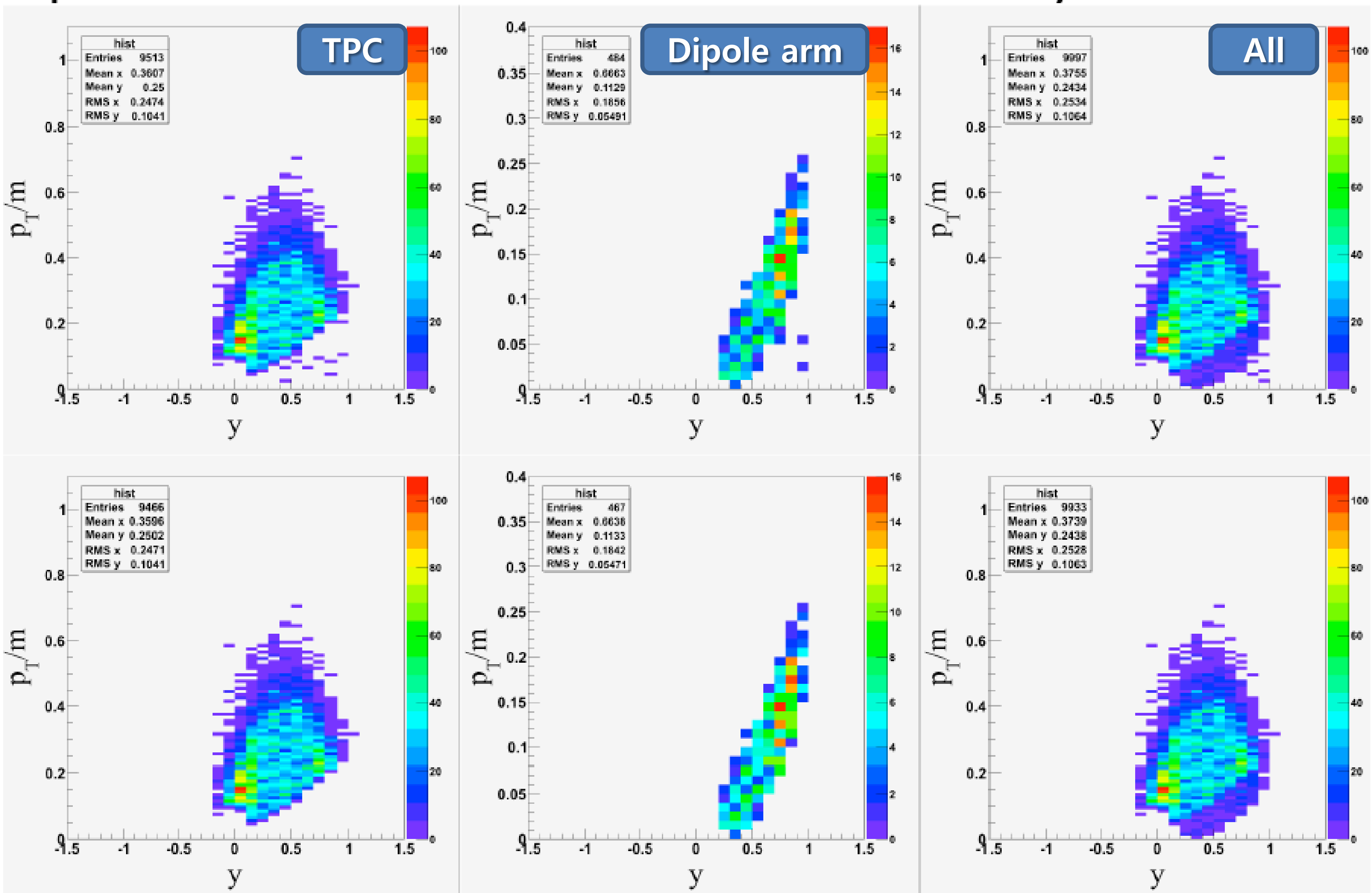
Hough transformation for particles tracking in TPC



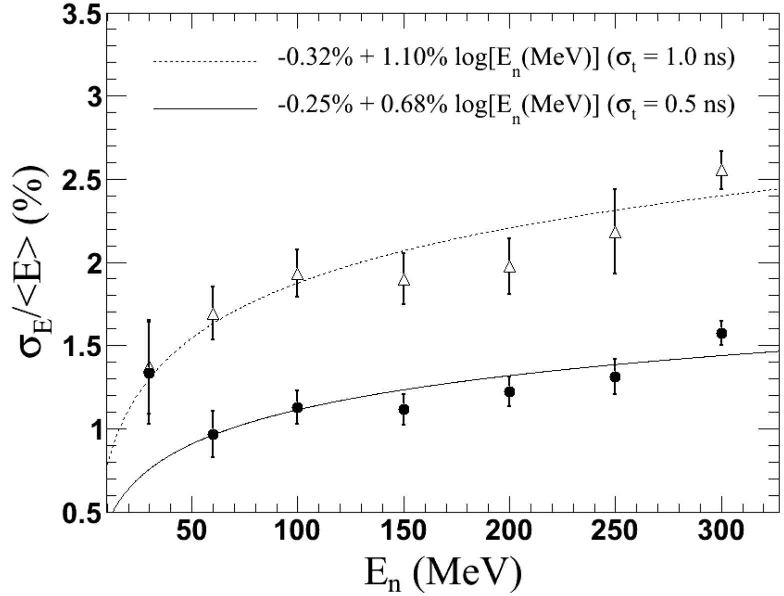
deuteron 400 MeV Soft Model w/ Secondary



alpha 400 MeV Soft Model w/ Secondary

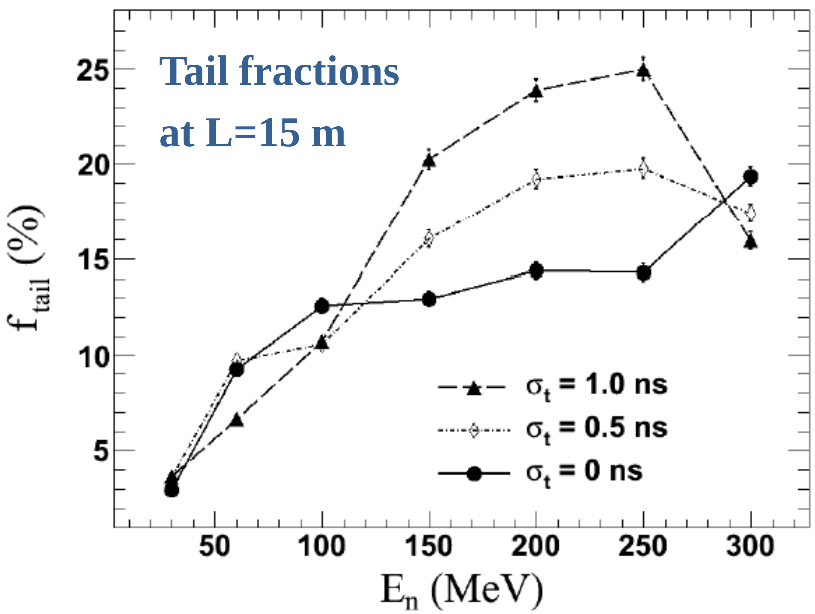


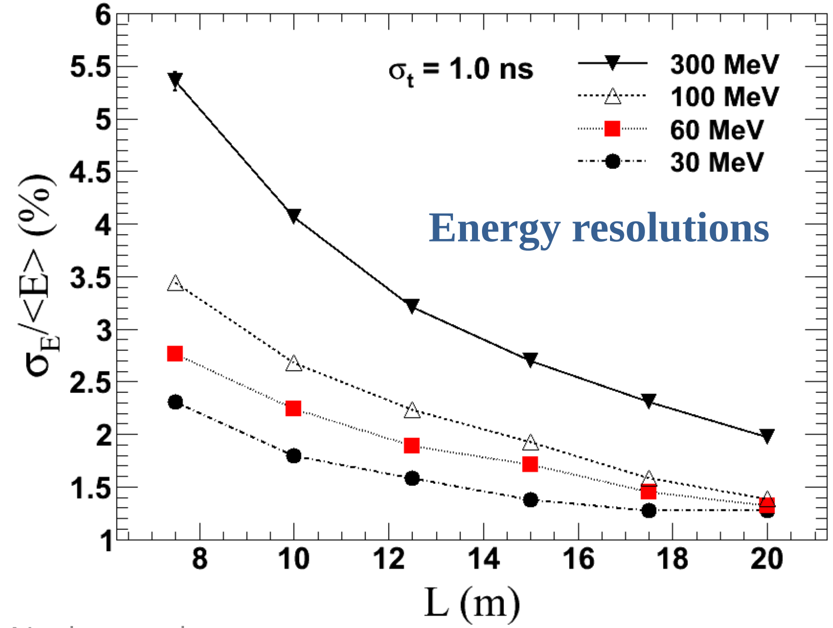
Energy resolution at L=15 m



GEANT4 simulation results

⇒ JKPS





IFF Linac Beam Specification

Ion Species	Z/ A	Ion source output		SC linac output			
		Charge	Current (pμA)	Charge	Current (pμA)	Energy (MeV/u)	Power (kW)
Proton	1/ 1	1	660	1	660	610	400
Ar	18/ 40	8	42.1	18	33.7	300	400
Kr	36/ 86	14	22.1	34-36	17.5	265	400
Xe	54/ 136	18	18.6	47-51	12.5	235	400
U	92/ 238	33-34	11.7	77-81	8.4	200	400

Estimated RIBs based on ISOL

Isotope	Half-life	Yield at target (pps)	Overall eff. (%)	Expected Intensity (pps)
^{78}Zn	1.5 s	2.75×10^{10}	0.0384	1.1×10^{7}
^{94}Kr	0.2 s	7.44×10^{11}	0.512	3.8×10^{9}
^{97}Rb	170 ms	7.00×10^{11}	0.88	6.2×10^{9}
^{124}Cd	1.24 s	1.40×10^{12}	0.02	2.8×10^{8}
^{132}Sn	40 s	4.68×10^{11}	0.192	9.0×10^{8}
^{133}In	180 ms	1.15×10^{10}	0.184	2.1×10^{7}
^{142}Xe	1.22 s	5.11×10^{11}	2.08	1.1×10^{10}