Nuclear Physics School for Young Scientists (NUSYS-2019)
Institute of Modern Physics (IMP), Lanzhou, China
August 12-17, 2019

Current Status of RAON & Nuclear Physics Experiments

Byungsik Hong (洪炳軾)
Korea University (高麗大學)

RISP Rare Isotope Science Project

RAON

CENuM Center for Extreme Nuclear Matters

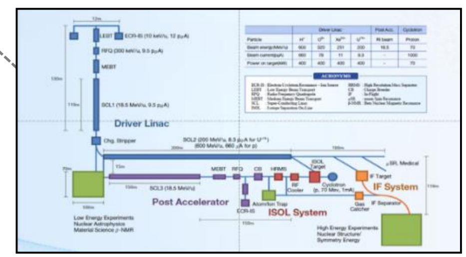
KOREA UNIVERSITY 1905

Overview of Rare Isotope Science Project

- **Goal :** To build **a heavy-ion accelerator complex, RAON,** in Korea for **rare isotope science** research
  - RAON : Rare isotope Accelerator complex for ON-line experiments
- **Budget : KRW 1,432 billion (US\$ 1.26 billion, U\$ 1 ≈ KRW 1,200)**
  - Accelerators and experimental apparatus : 460.2 billion KRW
  - Civil engineering & conventional facilities : 972 billion KRW (incl. 357 billion KRW for purchasing land)
- **Period : Dec. 2011 ~ Dec. 2021**

System Installation Project

Development, installation, and commissioning of the accelerator systems that provides high-energy (200 MeV/u) and high-power (400kW) heavy-ion beams



Facility Construction Project

Construction of research and support facility to ensure stable operation of the accelerator and experiment systems and to establish a comfortable research environment (Accelerator & experiment buildings, supporting facility, administrative buildings, and guest house, etc.)

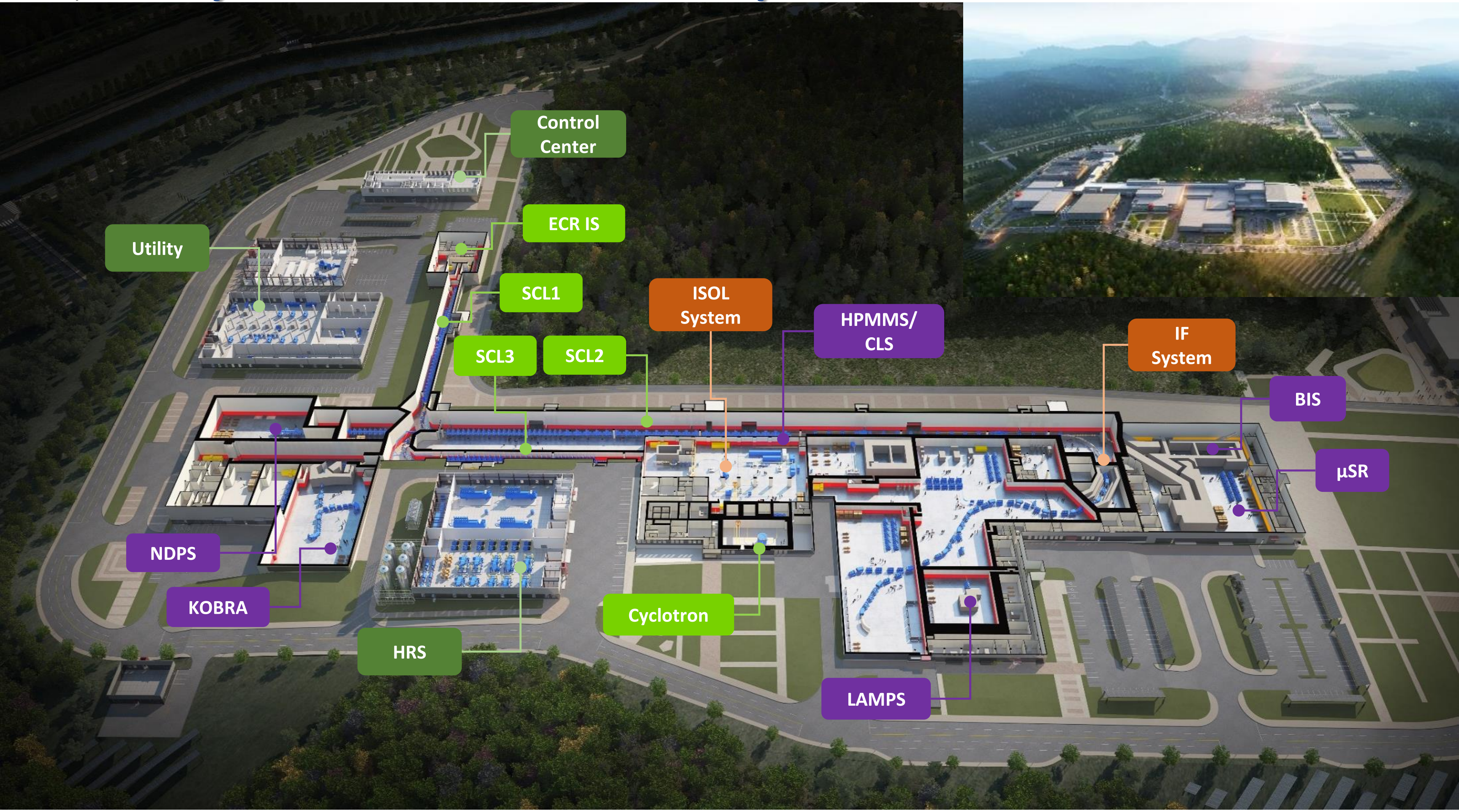
❖ Providing high intensity RIB by ISOL and IF
ISOL: direct fission of ^{238}U by 70 MeV p
IF: PF of 200 MeV/u ^{238}U at 8.3 pμA

❖ Providing high quality neutron-rich beams
e.g., ^{132}Sn at 250 MeV/u
~10^{8} particles per second

❖ Providing more exotic RIBs by combining ISOL and IF

Geographical information

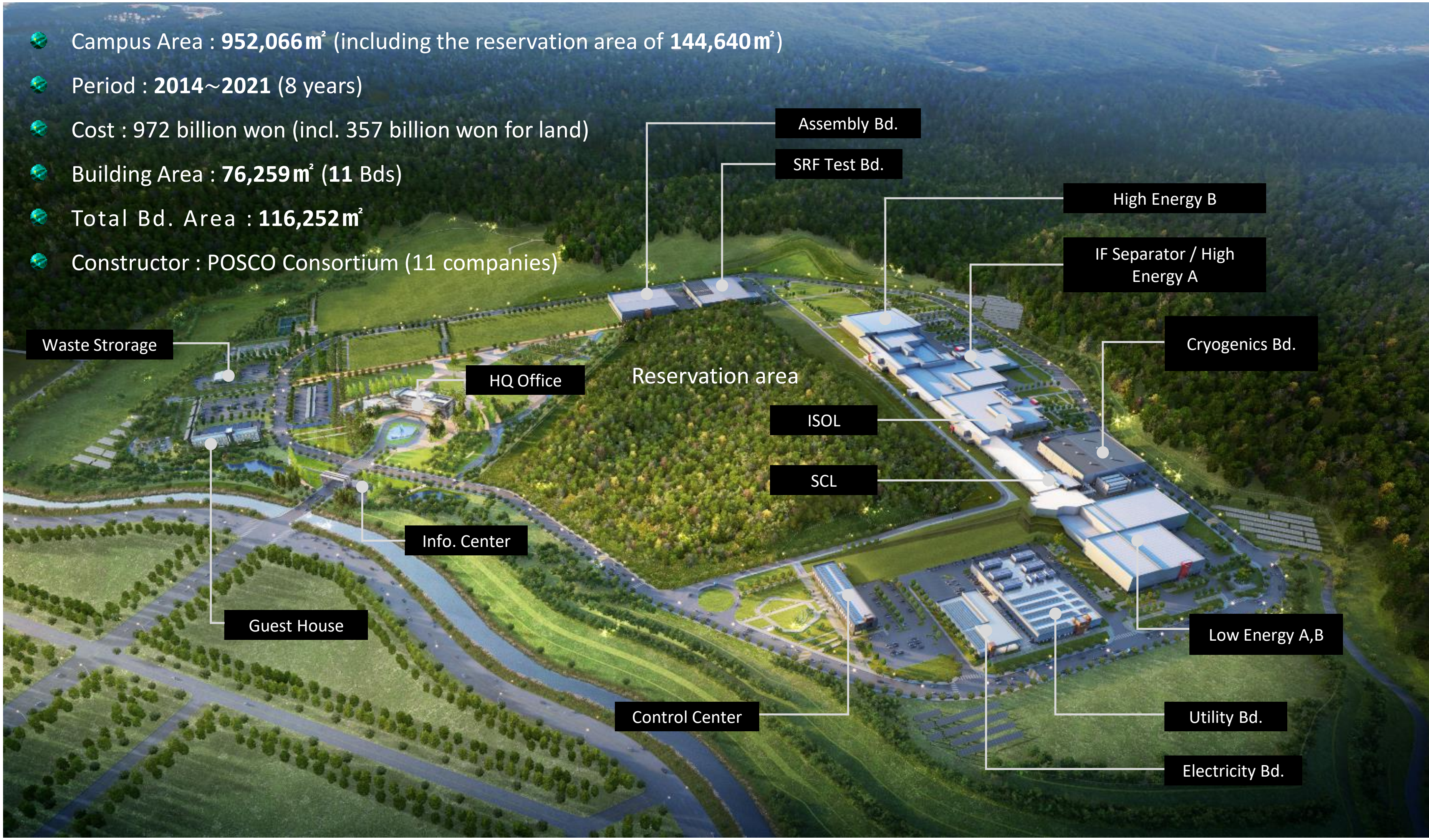
System installation plan



SCL1 has been postponed.
SCL3 will play the role of SCL1 for IF in early stage operation.

Facility construction plan (Buildings)

- Campus Area : **952,066㎡** (including the reservation area of **144,640㎡**)
- Period : **2014~2021** (8 years)
- Cost : 972 billion won (incl. 357 billion won for land)
- Building Area : **76,259㎡** (**11** Bds)
- Total Bd. Area : **116,252㎡**
- Constructor : POSCO Consortium (11 companies)



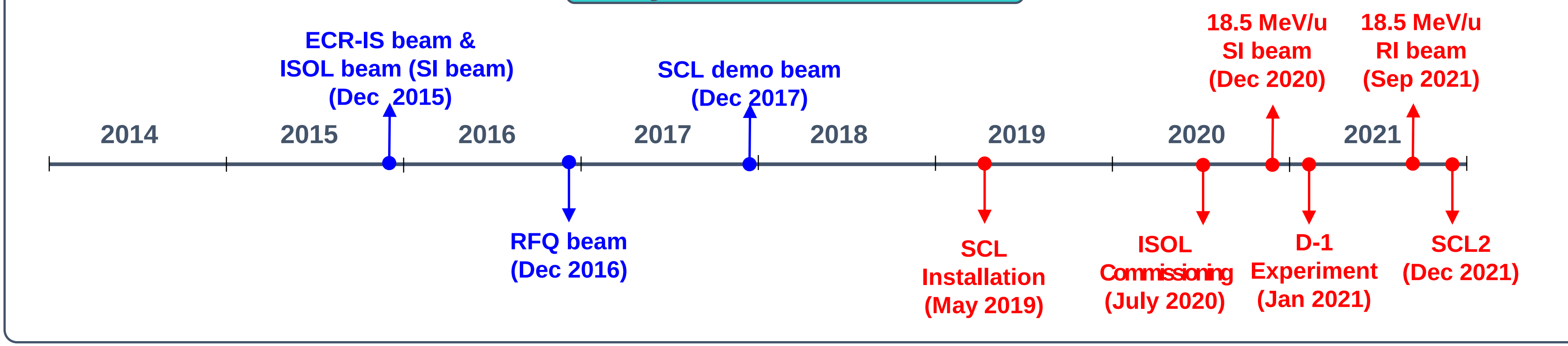
Some pictures of construction site

Milestones of RISP project

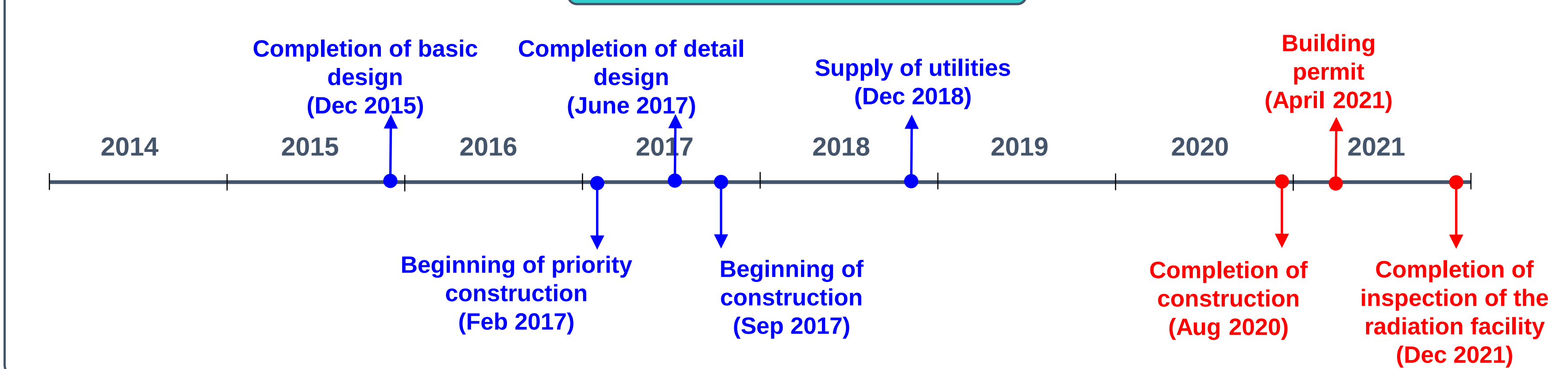
Rare Isotope Science Project

- (2018) SCL3 manufacturing SCL2 Prototype
- (2019) SCL3 Installation SCL2 manufacturing
- (2020) SCL3 Beam Commissioning/ Const. Completion
- (2021) SCL3 Beam Commissioning/ Project Completion

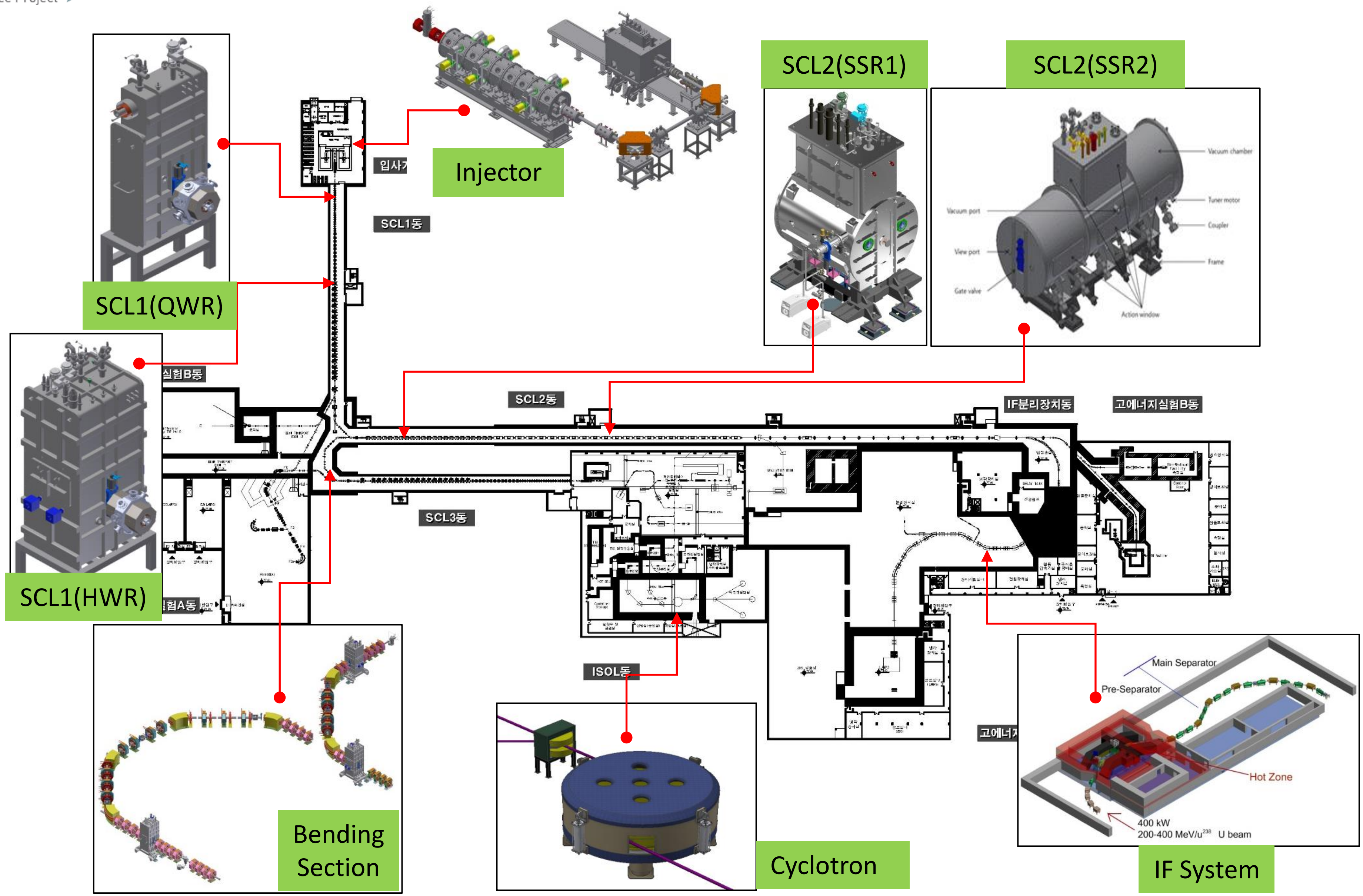
System Installation



Facility Construction

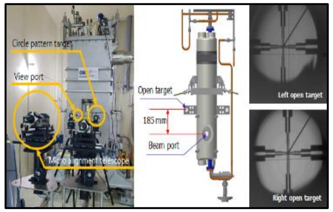


Accelerator systems



Major achievements

QWR cryomodule test completed (2017.05)



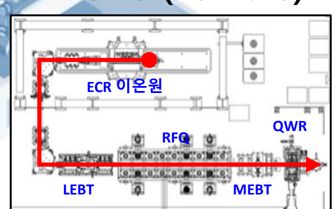
HWR cryomodule test completed (2018.03)

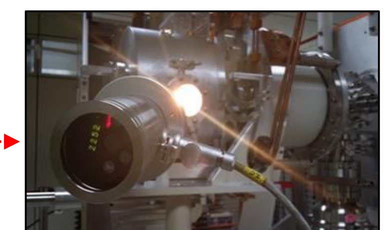
First Oxygen beam acceleration with RFQ (2016.12)

Low temperature test of quadrupole prototype magnets for IF: LTS (2016.01) & HTS (2017.01)

Superconducting RF test facility (2016.06)

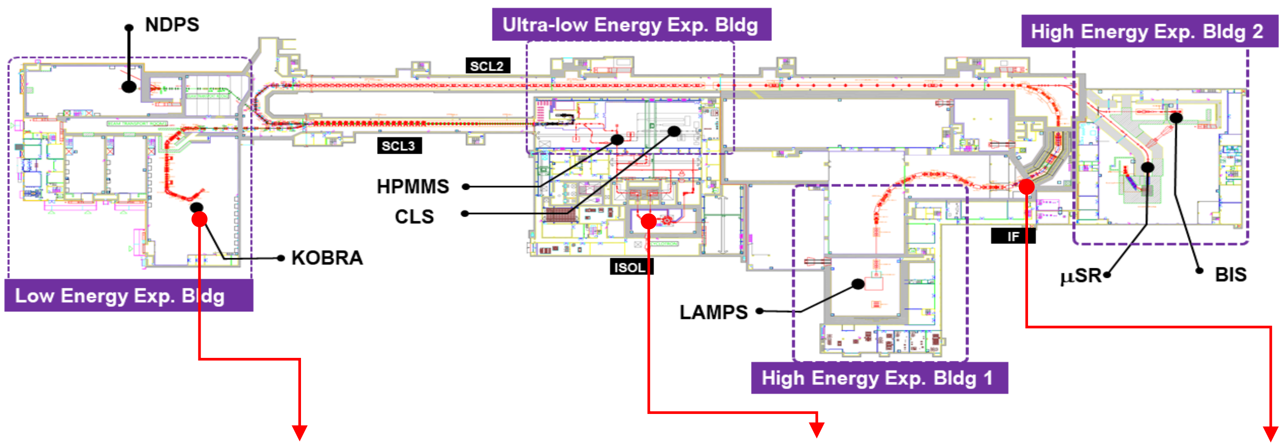
First Oxygen beam acceleration with QWR module, SCL Demo (2017.10)





High purity Sn beam extraction using RILIS (2015.12)

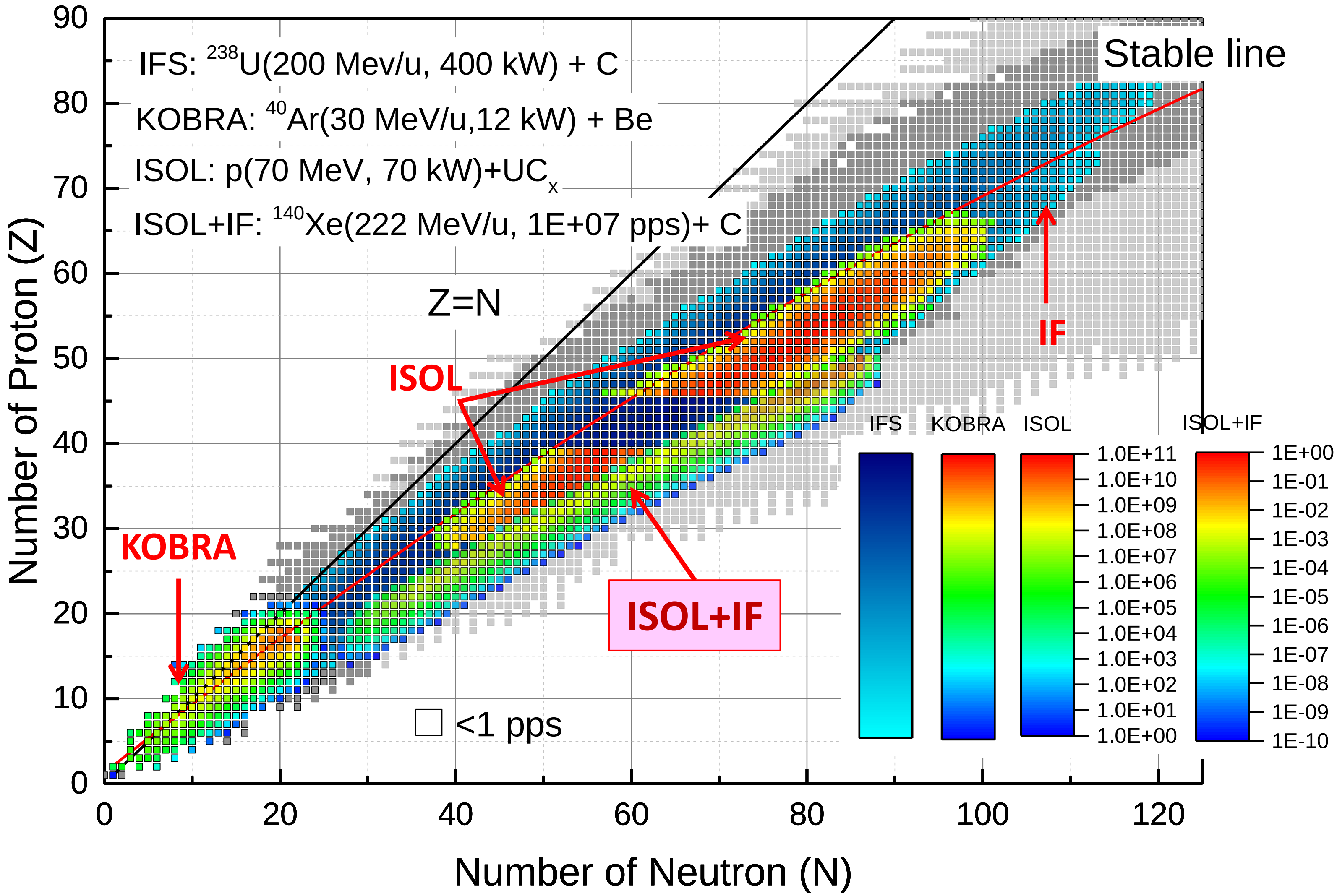
RIB production modes at RAON



	KOBRA (low-energy IF)	ISOL	IF (high energy)
Driver	(ECR) SCL3	Cyclotron	(ECR) SCL3→SCL2
Post accelerator		SCL3 (ultimately SCL3→SCL2)	
Production mechanism	• Direct reactions like (p, d), $({}^{3}\text{He}, n)$, etc. • Multi-nucleon transfer	p induced U fission	PF, U fission
RIB energy range	a few tens MeV/u	> a few keV/u	a few hundreds MeV/u

Various high-intensity RIBs in wide energy range are expected from RAON.

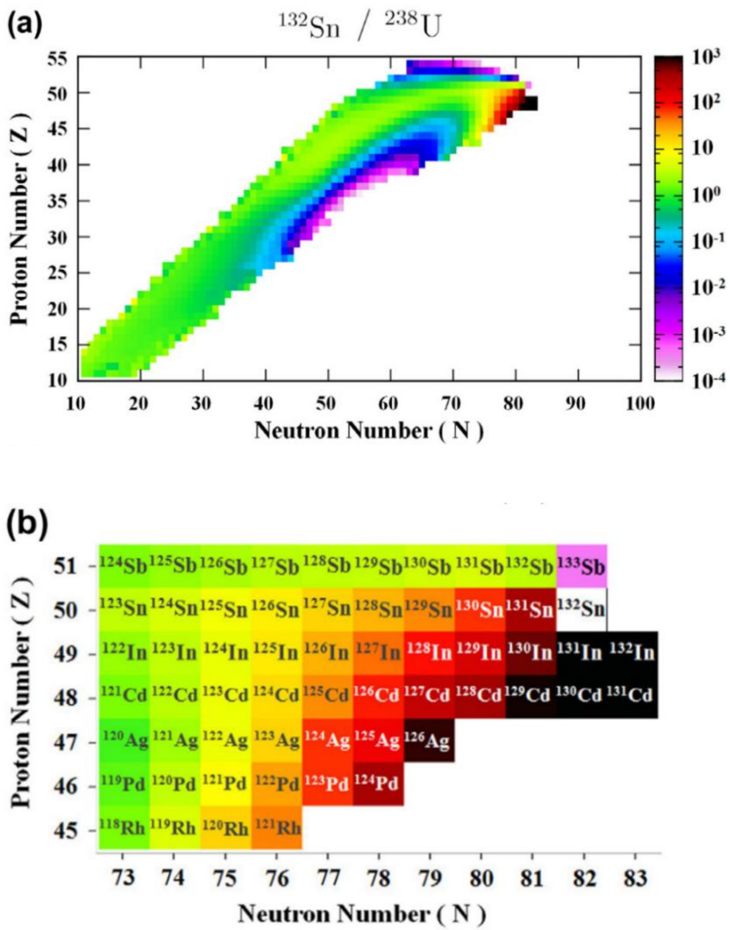
Expected RIBs at RAON



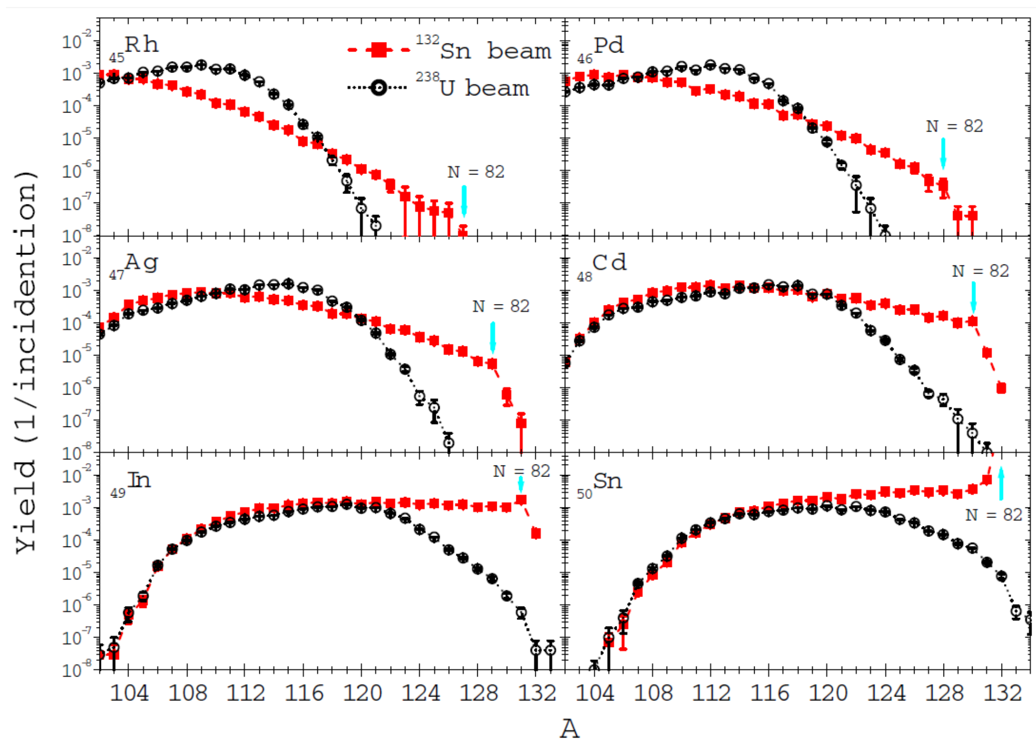
RAON aims to provide an access to unexplored regions of nuclear chart.

Expected RIBs at RAON

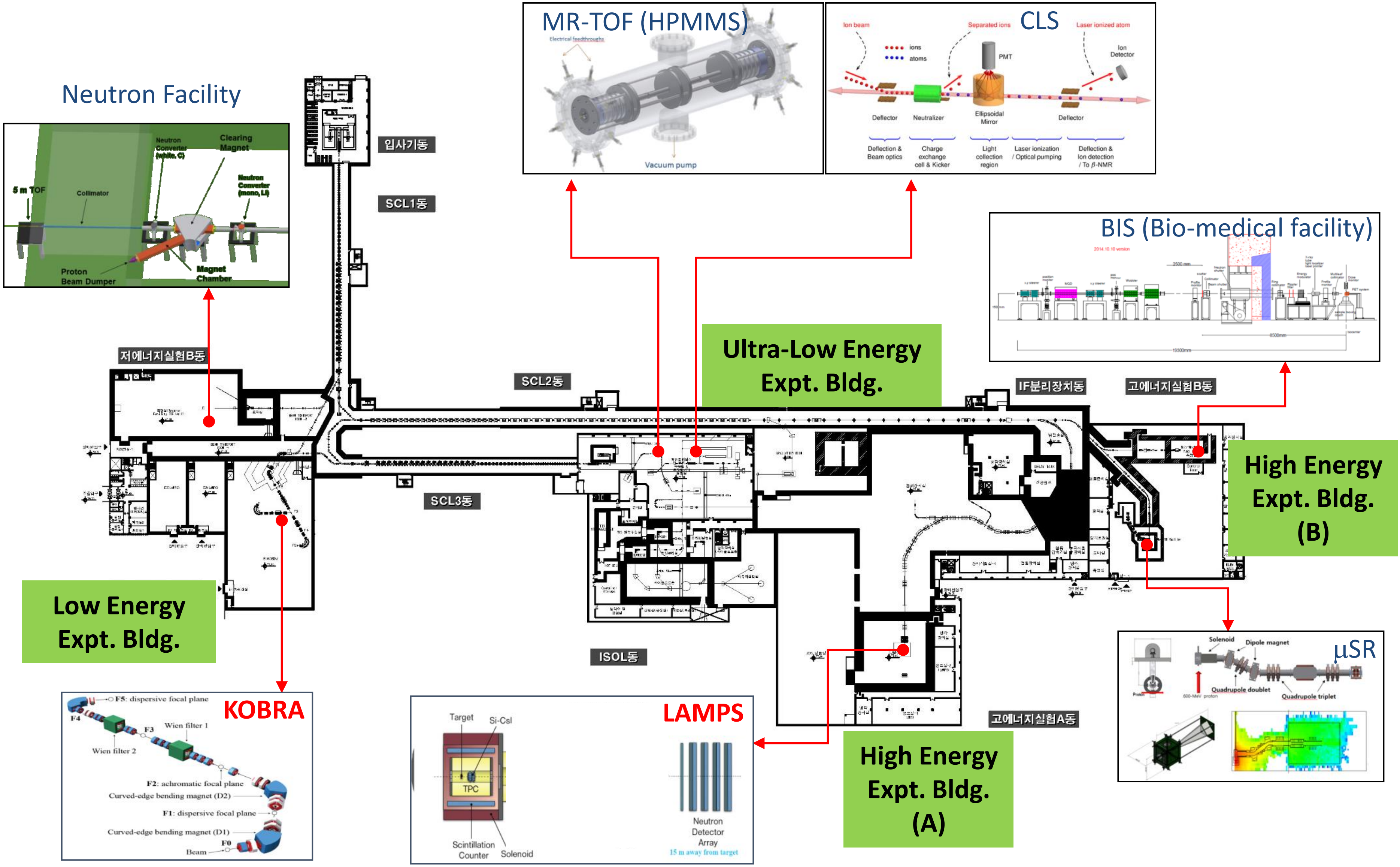
J.W. Shin et al., NIMB349, 221 (2015)



- ☐ Yield ratio: ^{132}Sn+^{9}Be/^{238}U+^{9}Be
- ☐ ISOL+IF is beneficial, for example, for n-rich isotopes for $45 \leq Z \leq 50$



Experimental systems

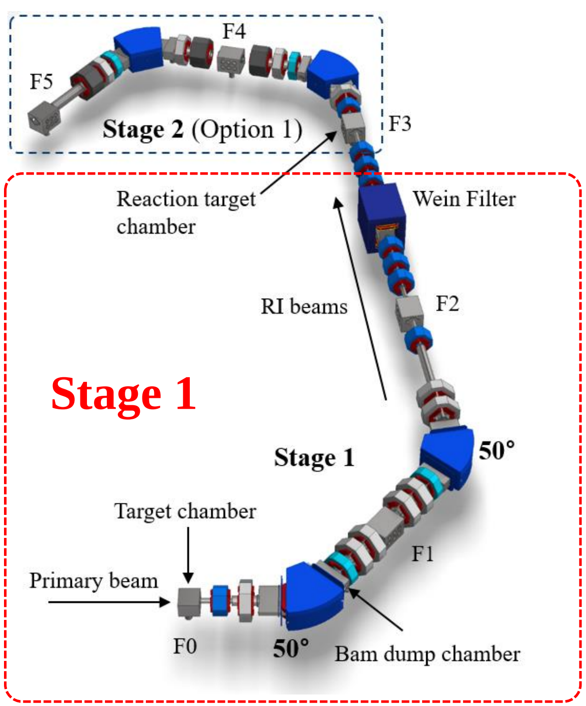


KOBRA

(KOrea Broad acceptance Recoil spectrometer and Apparatus)

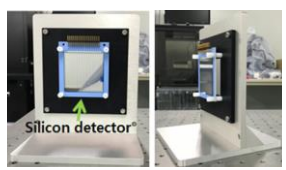
Conceptual design	Prototype & test	**Manufacturing**	Installation	Commissioning & Operation
2011~2012	~2017.9	**~2019.4**	~2020.12	2021.1~

- ☐ The first part of stage1 (stage1 part1) was contracted with foreign & domestic companies in April 2018. (Presently, the parts are being produced.)
- ☐ The stage1 will be installed in the low-energy Expt. hall (E1) by the end of June 2020.
- ☐ The commissioning of Stage1 will start in the beginning of 2021 with stable ion beams.



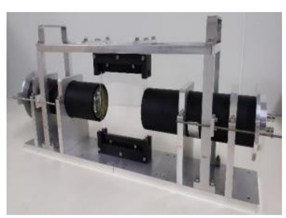
PPAC

- Two 10x10 cm^2, two 20x20 cm^2, and one 40x20 cm^2 active area PPACs were built.
- Four 10x10 cm^2 and one 40x20 cm^2 PPACs will be built in addition.



SSD

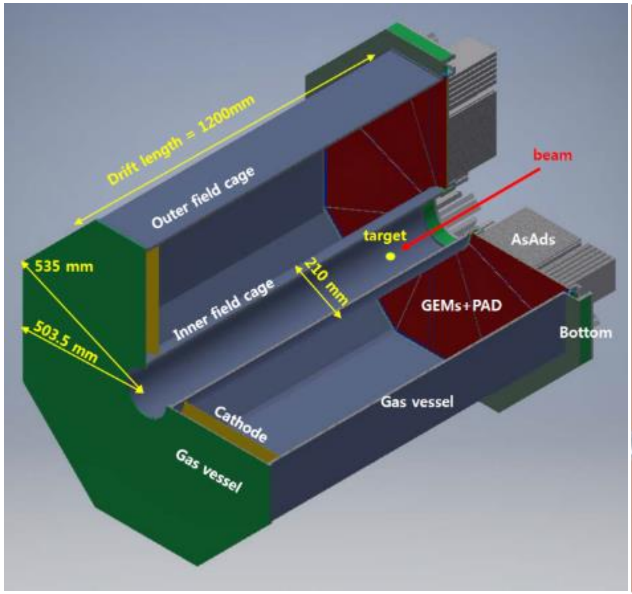
- Two 16 Channel detectors with 5x5 cm^2 active area and 50 μm thickness
- Energy resolution~0.7% and S/N~272 for 5.5 MeV α in vacuum

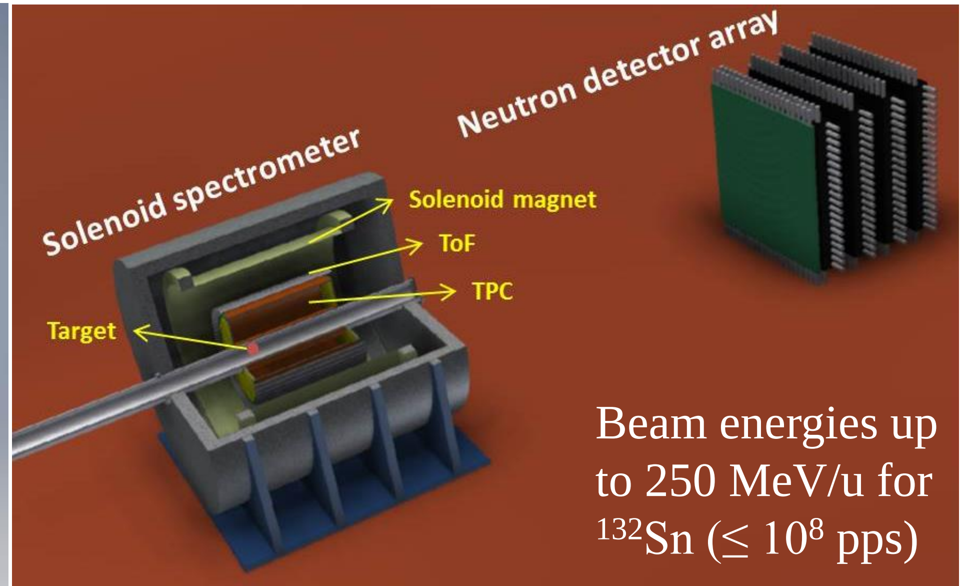


Plastic scintillator detector

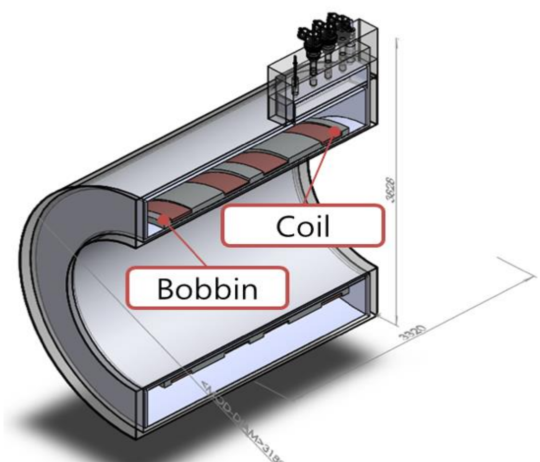
- Two detectors read out both ends with 10x10 cm^2 active area and 100 μm thickness
- Time resolution < 42 ps for 5.5 MeV α in vacuum

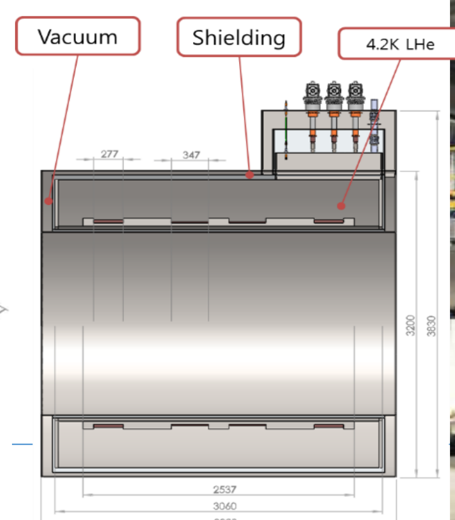
LAMPS: Large-Acceptnce MultiPurpose Spectrometer



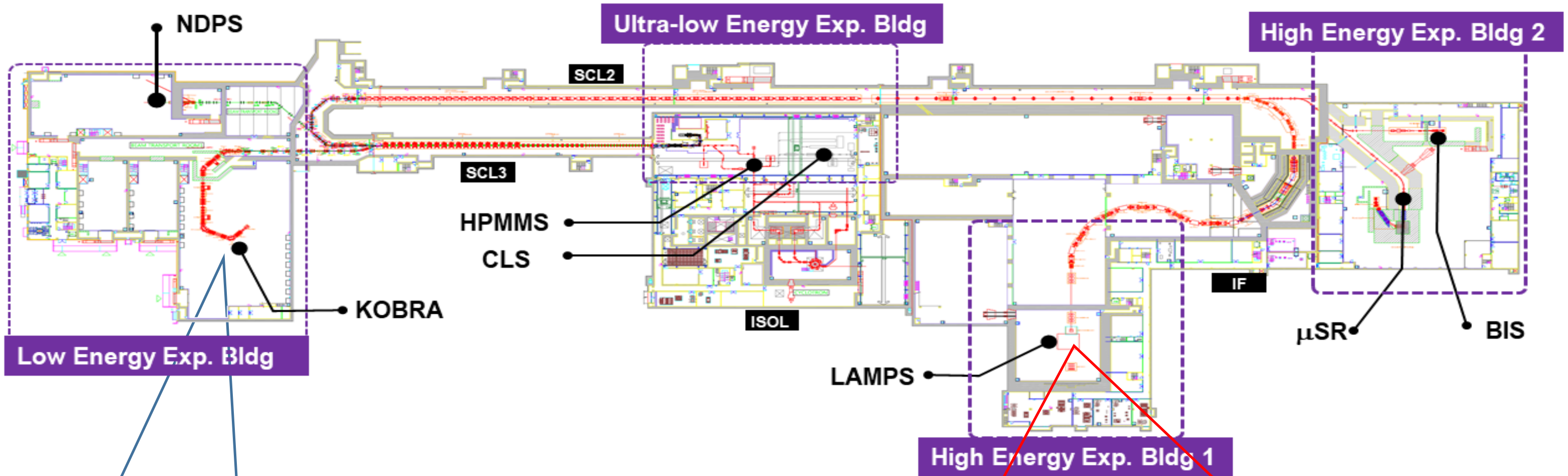


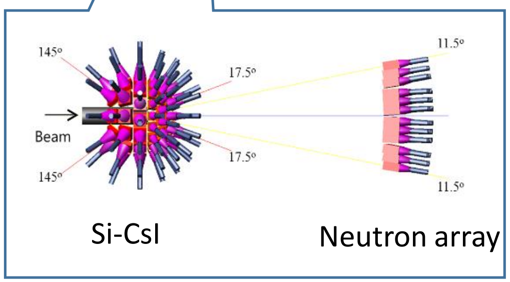
Beam energies up to 250 MeV/u for ^{132}Sn ($\leq 10^8$ pps)

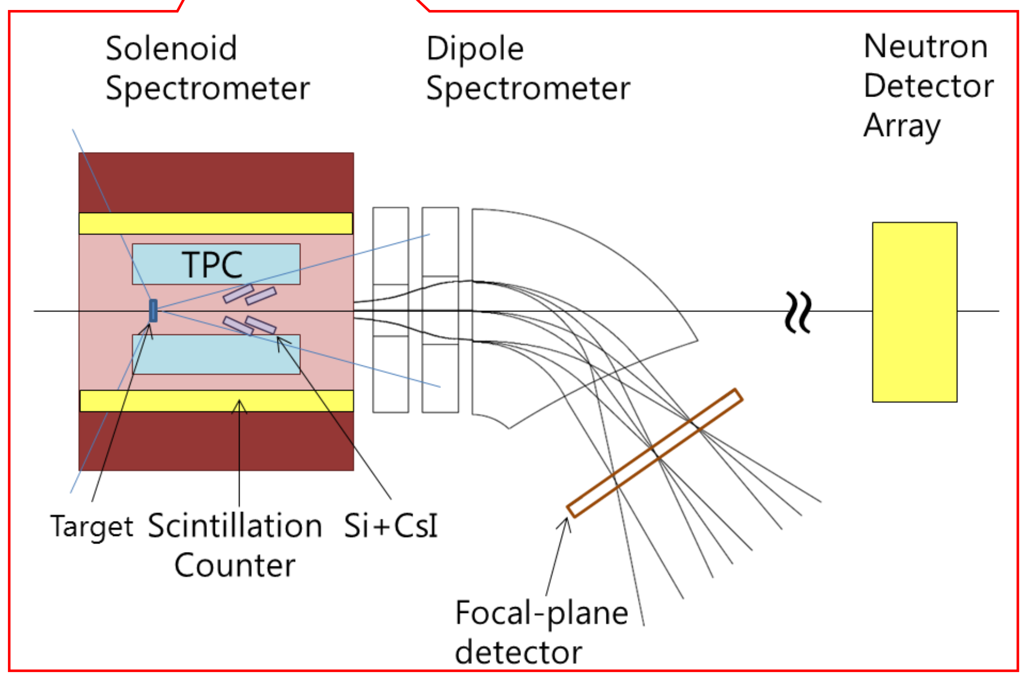




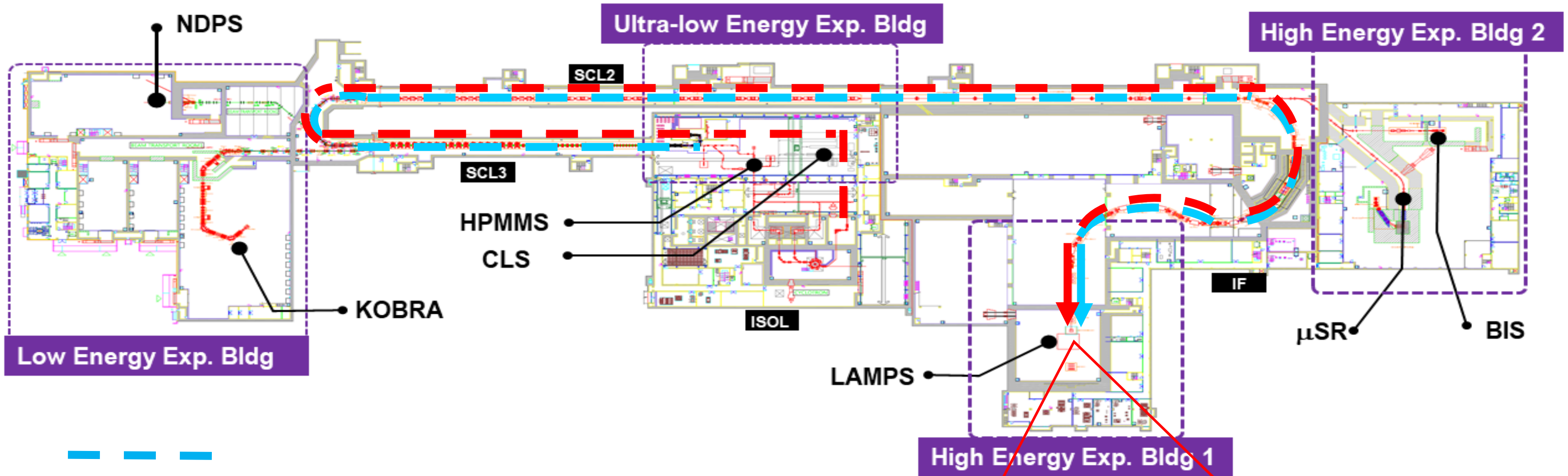
Brief history of LAMPS







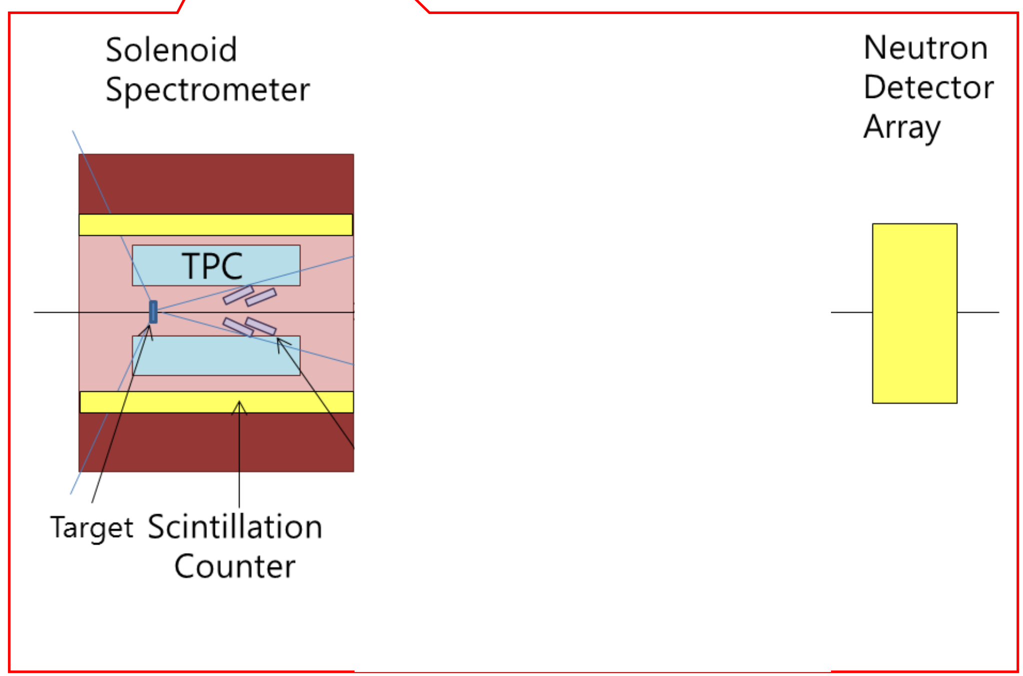
Brief history of LAMPS



Stable-ion initiation modes
(i) ECR→SCL3 → SCL2 →LAMPS
(ii) ECR→SCL3 → SCL2 →IF Target →LAMPS

RIB initiation modes
(iii) ISOL→SCL3 →SCL2→LAMPS
(iv) ISOL→SCL3 →SCL2→IF Target →LAMPS

LAMPS will cover maximal area of beam species in the nuclear chart.



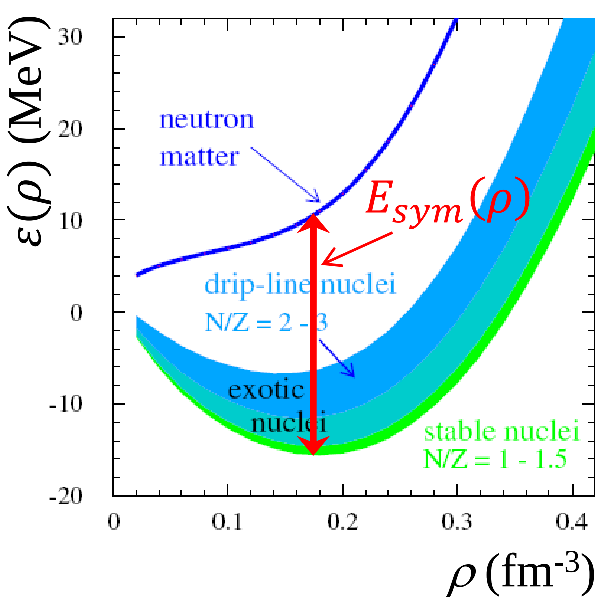
Physics goal: EoS and symmetry energy

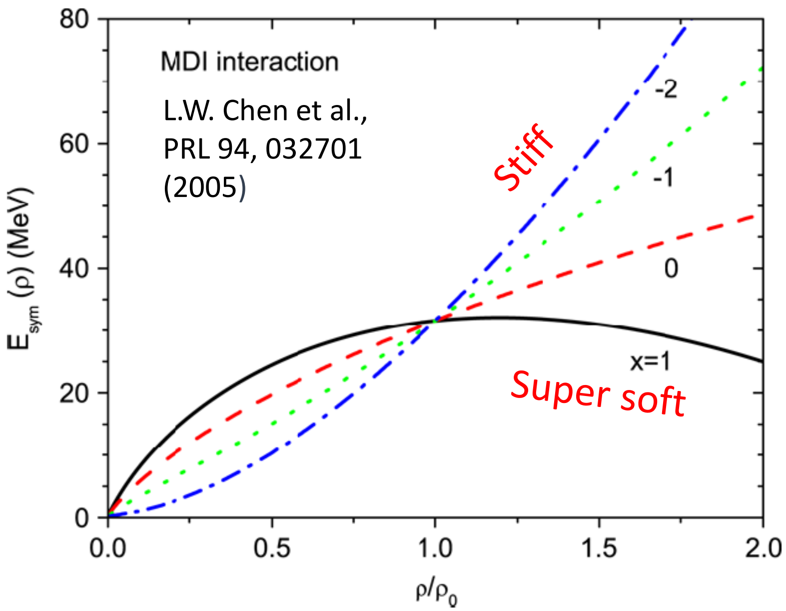
- General approach
  - Investigate the energy per nucleon $E/A = \varepsilon(\rho, \delta)$ as functions of baryon density ρ and isospin asymmetry $\delta = (N-Z)/(N+Z)$:

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

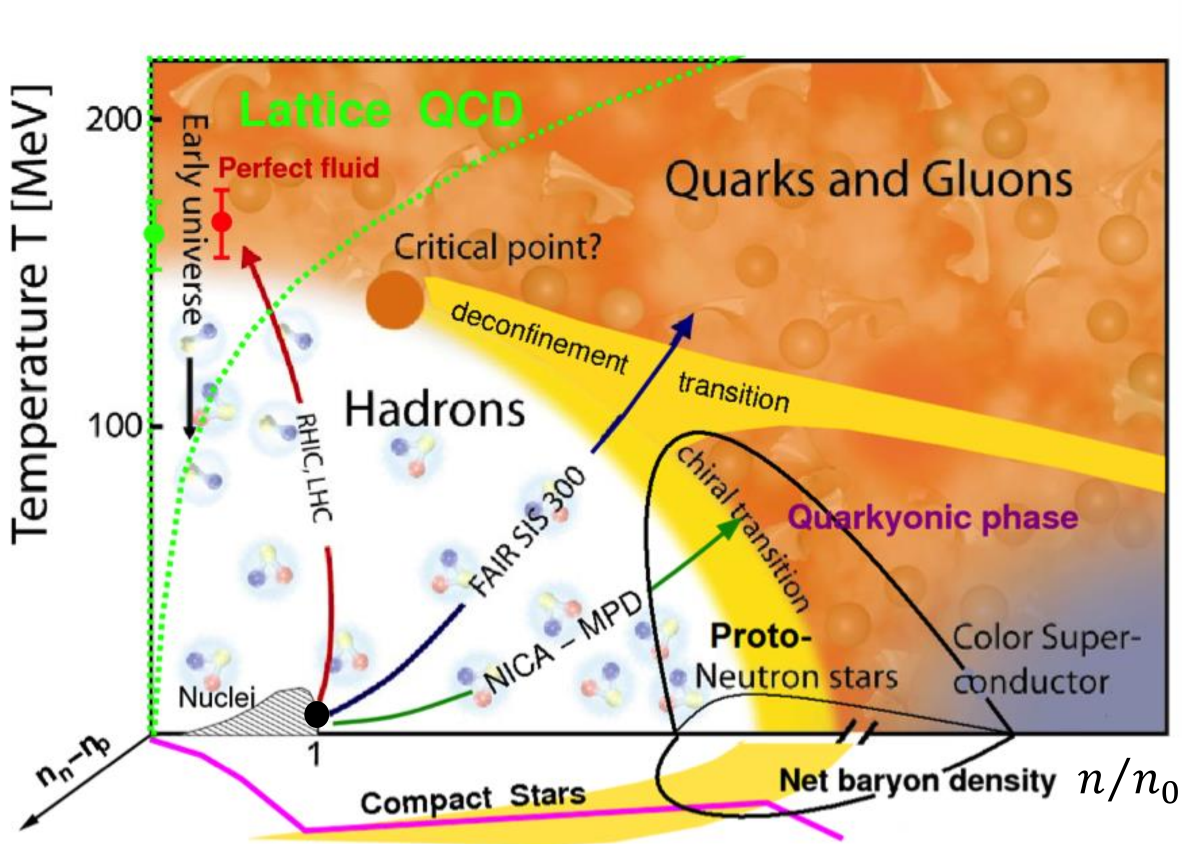
with $E_{sym}(\rho)$ the symmetry energy

- Theoretical approach
  - Calculate $\varepsilon(\rho, \delta)$ by some density functionals or variational calculations
- Experimental approach
  - Constrain EoS and $E_{sym}(\rho)$ using controlled laboratory experiments at specific ρ





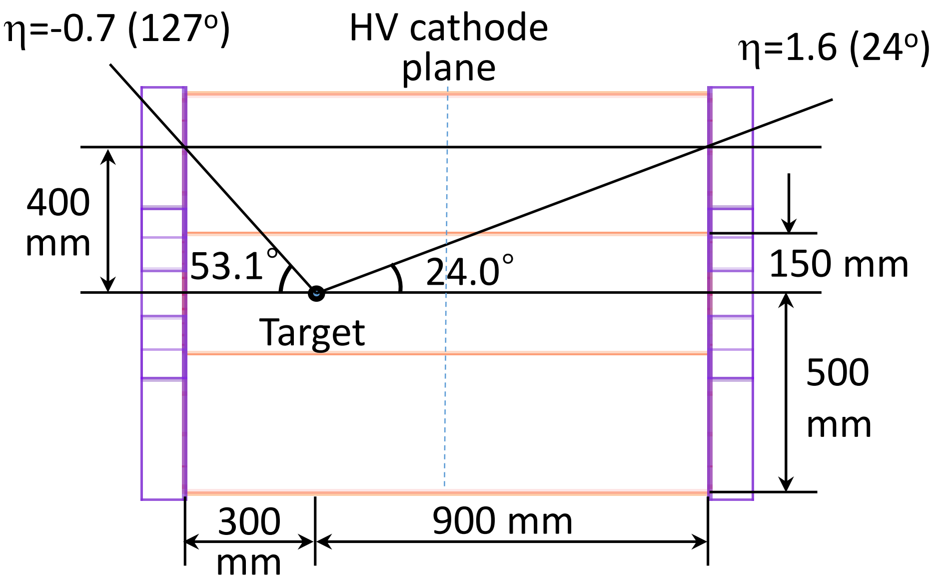
Physics goal: Nuclear phase diagram



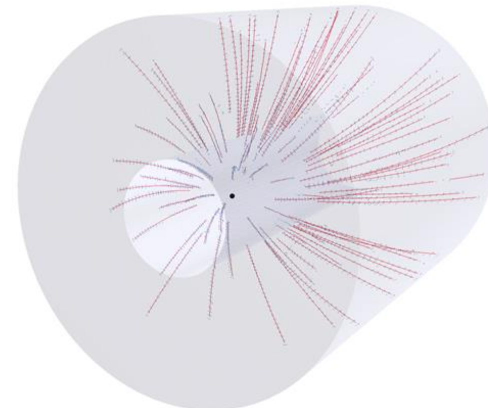
- Why are we doing heavy-ion collision experiment?
  → Only way to create dense (and hot) nuclear matter at laboratories
- Why are we using RI beams for heavy-ion collision?
  → Only way to control the isospin parameter (*N/Z*) of matter

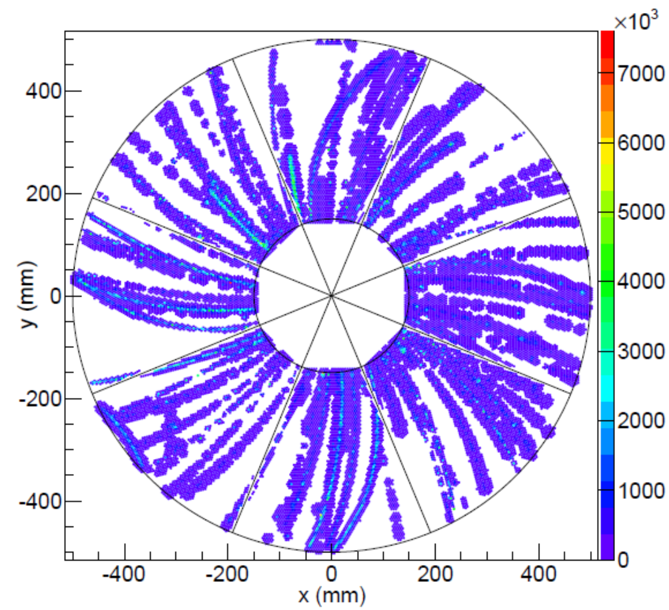
Time Projection Chamber (TPC)

Original design



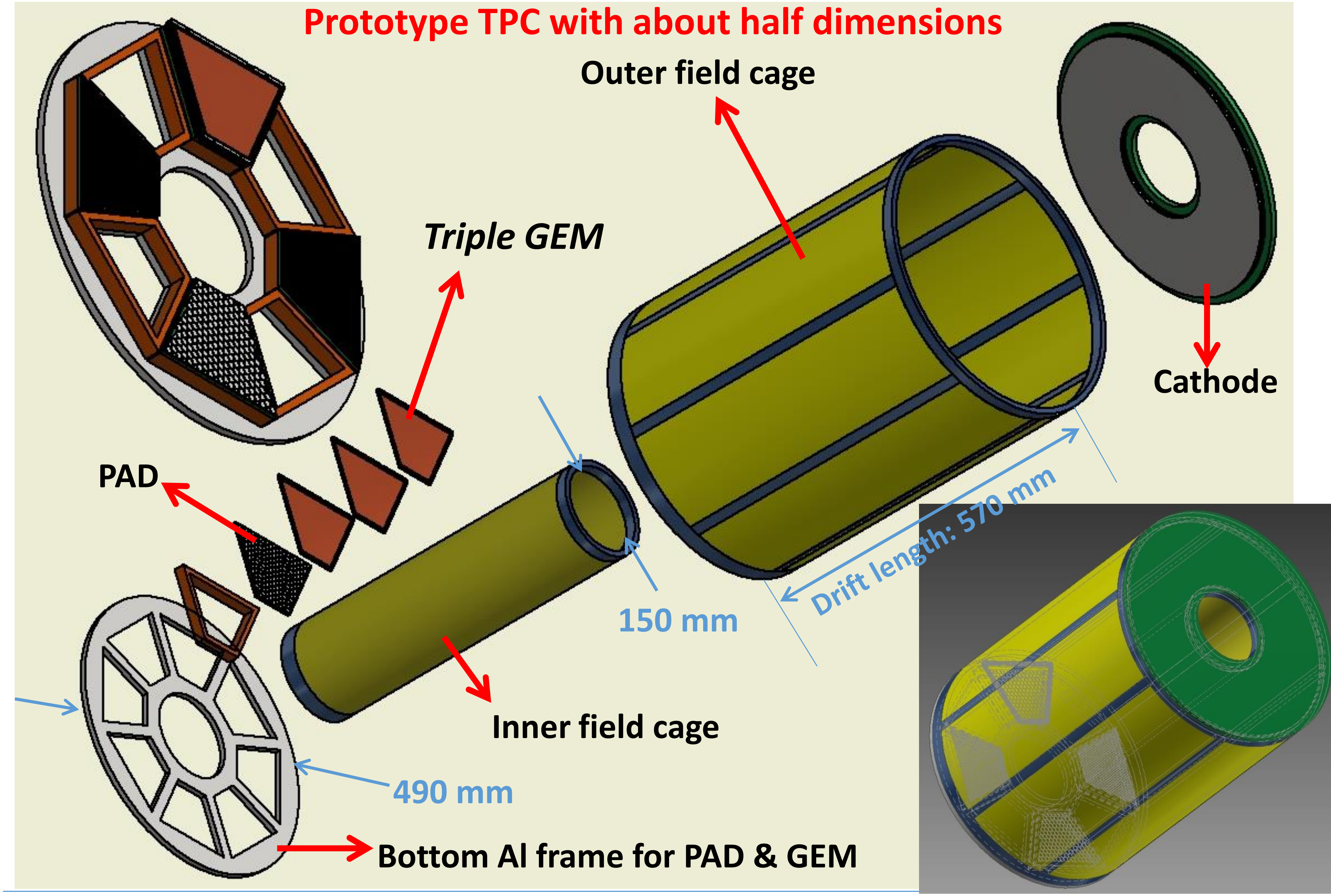
Simulation of a central Au+Au event at 250 AMeV (IQMD)





- 3-D tracking device for charged particles
- Large acceptance (~3π sr)
- Symmetric in azimuthal angle
- Triple GEM system for amplification
- Read readout at both endcaps
  (Total # of channels ~30k)

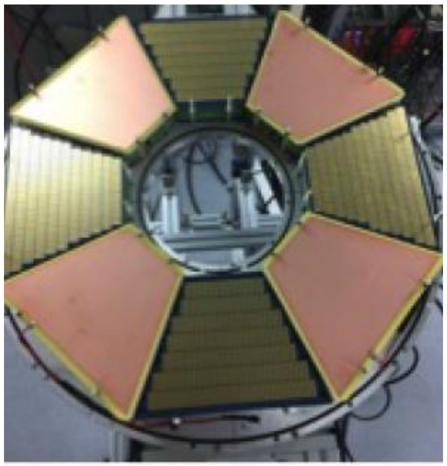
TPC: Prototype design

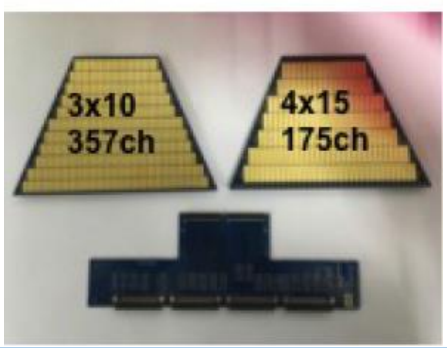


Rare Isotope Science Project

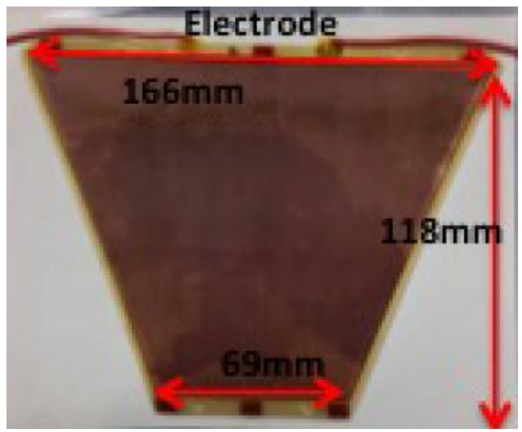
TPC: Components

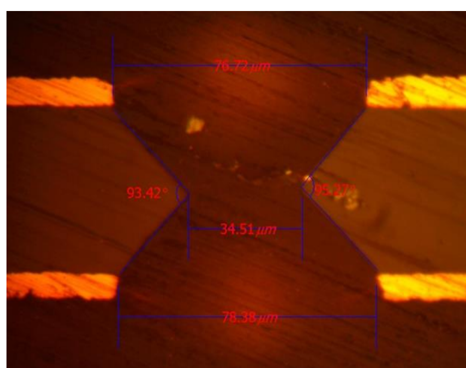
[Readout Pads]
Tested pads with the two different dimensions
$3 \times 10\ \mathrm{mm}^2$: 357 Ch/Sec
$4 \times 15\ \mathrm{mm}^2$: 175 Ch/Sec
Multi-layer PCB board

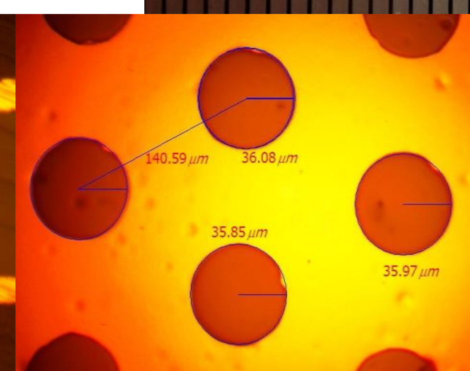




[GEM Foil]
Trapezoidal shape
Thickness: 75 μm
Area: $166 \times 118\ \mathrm{mm}^2$
Triple layers for each plane
Developed for CMS at LHC



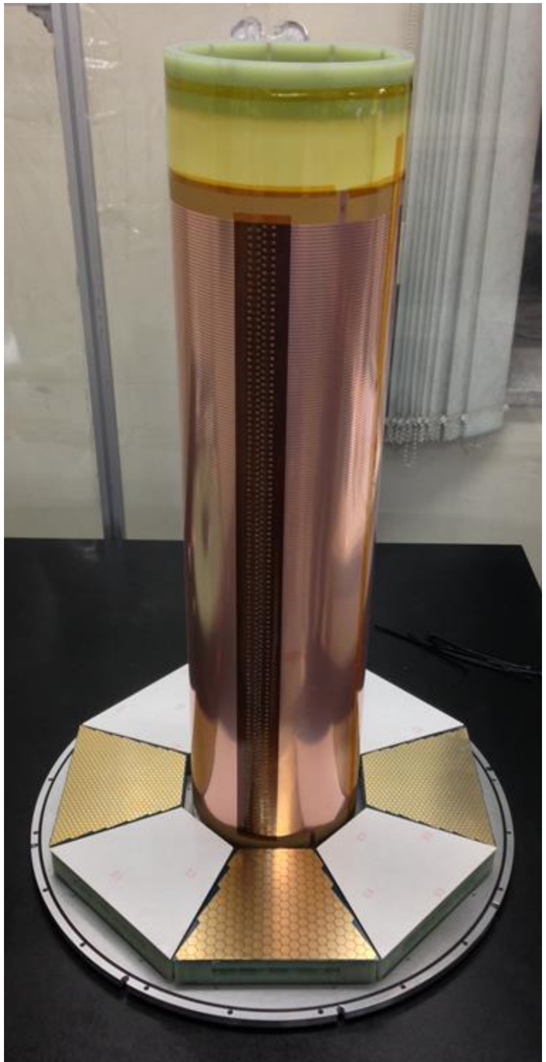




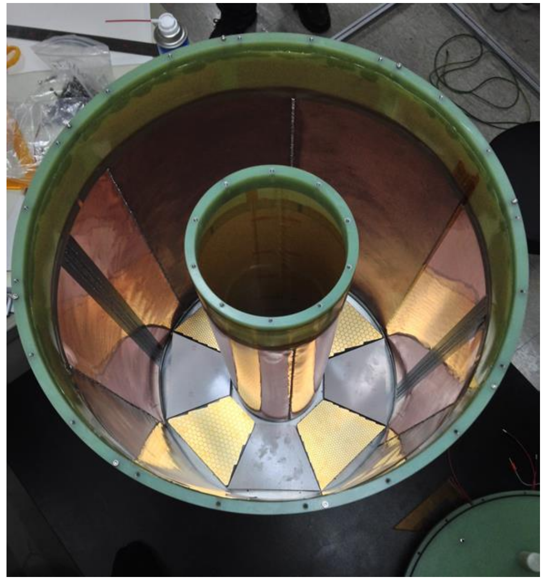
[Field Cage]
35 μm thick and 2 mm wide Cu strips
500 μm gap between adjacent strips
Mirror strips on the back
1 MΩ resistors with 0.1% variance
TPC body: G10 + Aramid honeycomb

TPC: Assembly

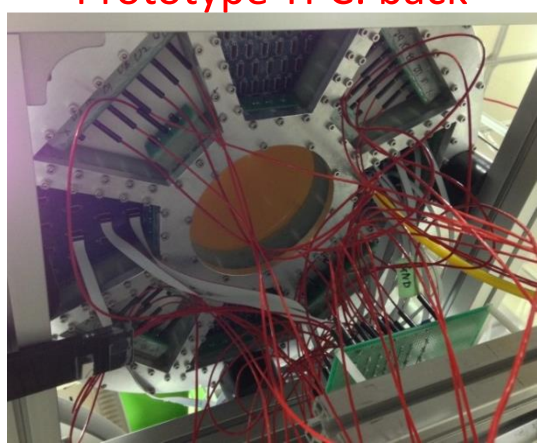
Inner field cage installed



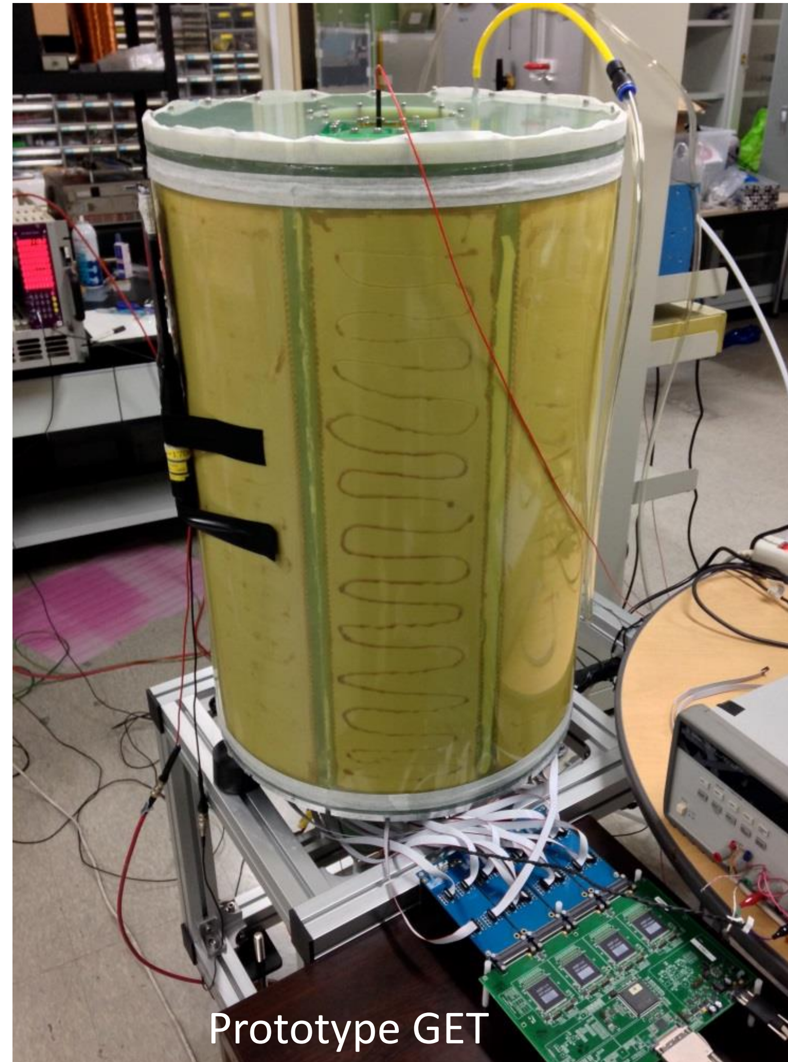
Outer field cage installed



Prototype TPC: back



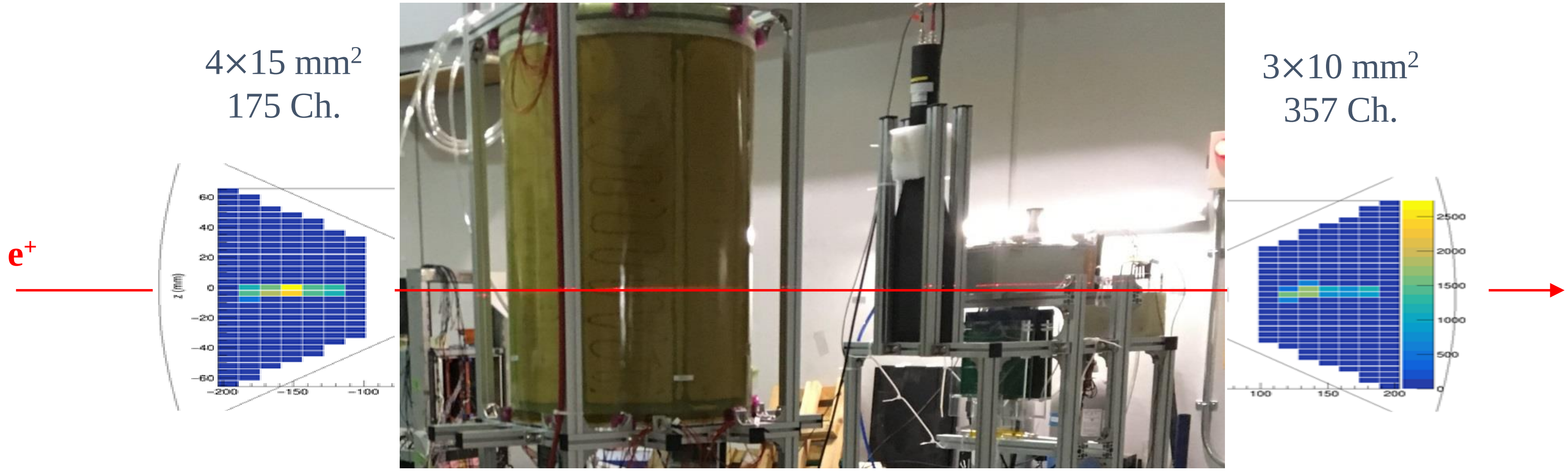
Prototype TPC completed

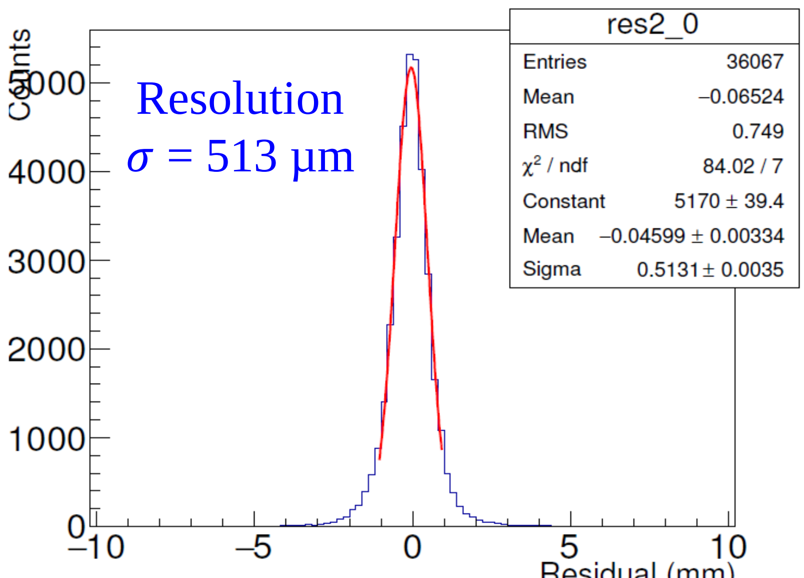


TPC: Beam test at ELPH

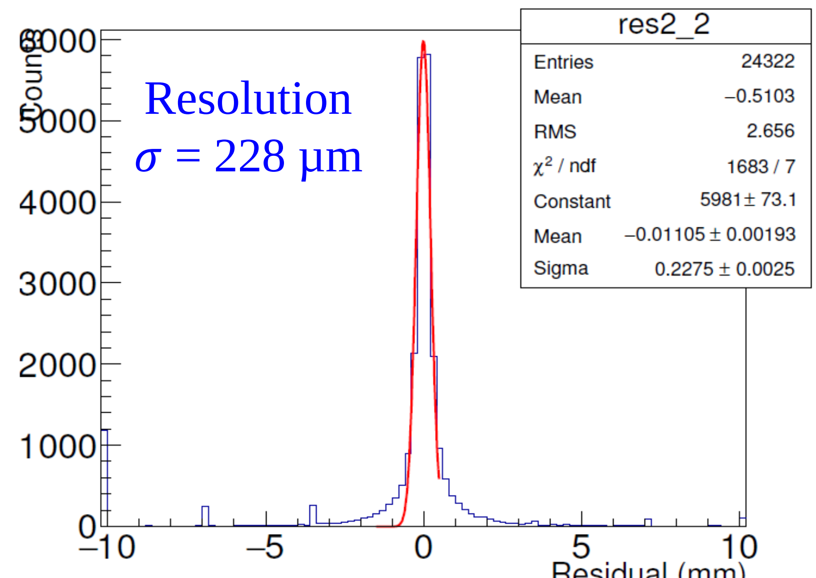
- ☐ ELPH: Research Center for Electron Photon Science at Tohoku University, Japan
- ☐ Dates: November 2016
- ☐ Beams: e^+ beams at 500 MeV
- ☐ Gas: Ar(90%)+CH_4(10%) (P10)
  Ar(90%)+CO_2(10%) ($ArCO_2$)
- ☐ Purpose: To study the detailed characteristics, such as v_{drift}, diffusion and σ_x, of LAMPS TPC

TPC: Position resolution





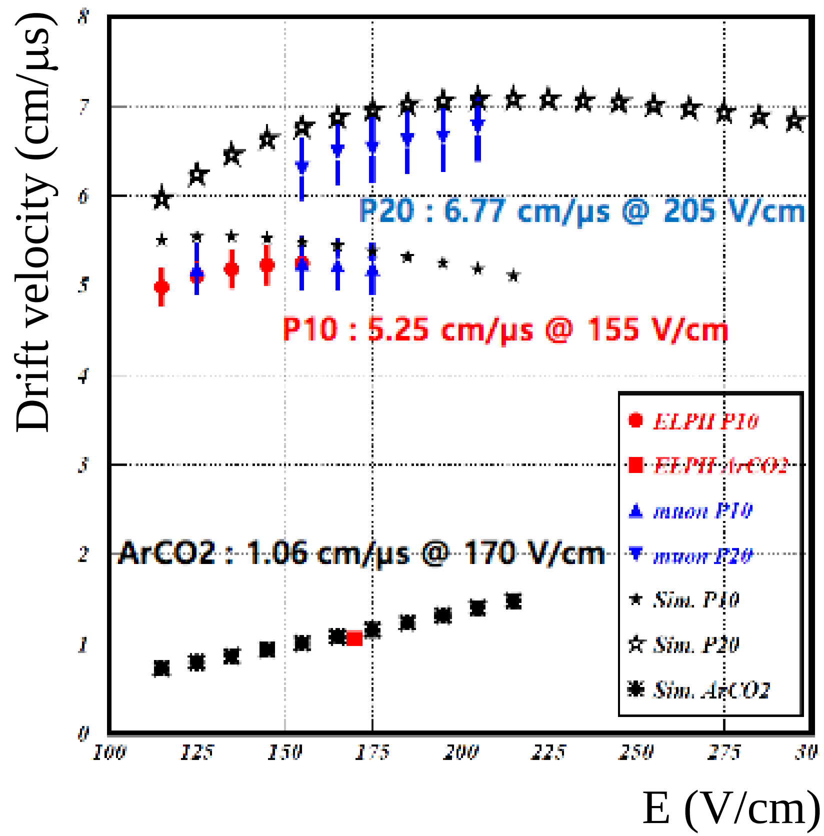
4×15 mm² pad



3×10 mm² pad

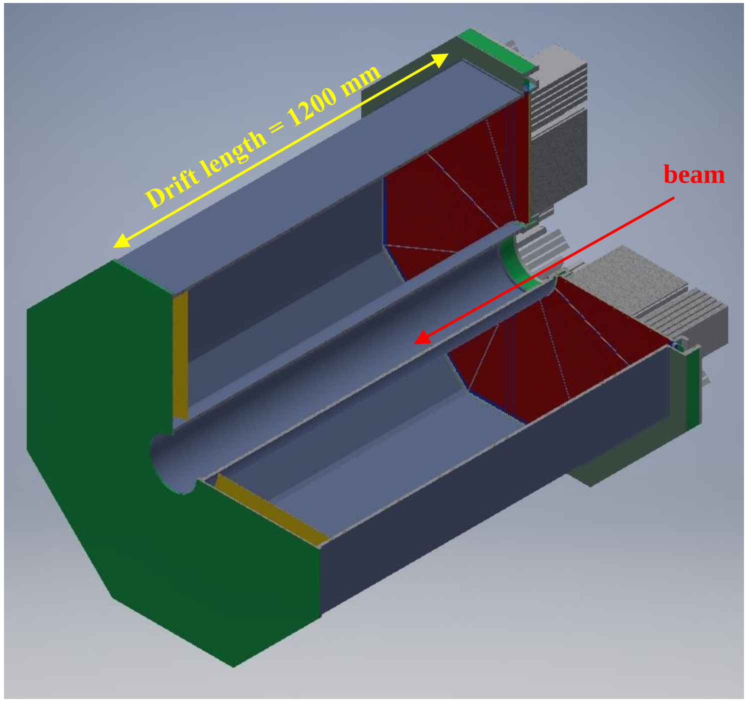
TPC: Drift velocity

- **ELPH beam test**
  - Beam height: 20.24, 35.24 & 50.24 cm
  - Electric field:
    115~155 V/cm for Ar-CH_4(90:10)
    170 V/cm for Ar-CO_2(90:10)
- **Cosmic-ray muon test**
  - Trigger counter: 4 cm & 20 cm
  - Electric field:
    155~175 V/cm for Ar-CH_4(90:10)
    155~205 V/cm for Ar-CH_4(80:20)

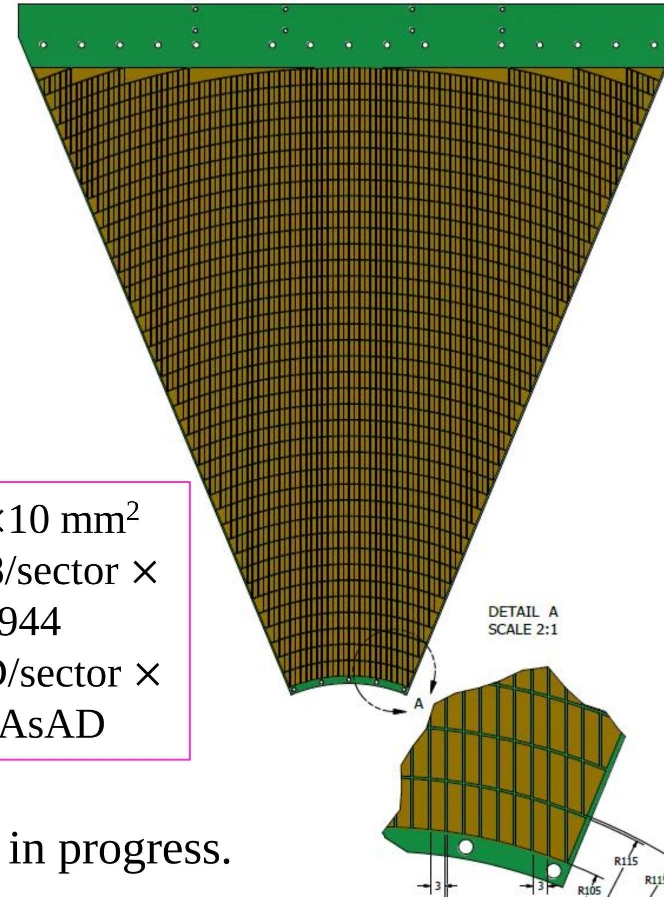


- $v_{drift} \lesssim 5.3$ cm/μs for P10 from the beam test:
  Maximum distance: 512 timing bins $\times$ 0.04 μs/bin $\times$ 5 cm/μs $\cong$ 100 cm
- P20 with cosmic muons: $v_{drift} > 6$ cm/μs that is suitable for LAMPS TPC if we want to read out signals only from the upstream endcap.

TPC: Final design

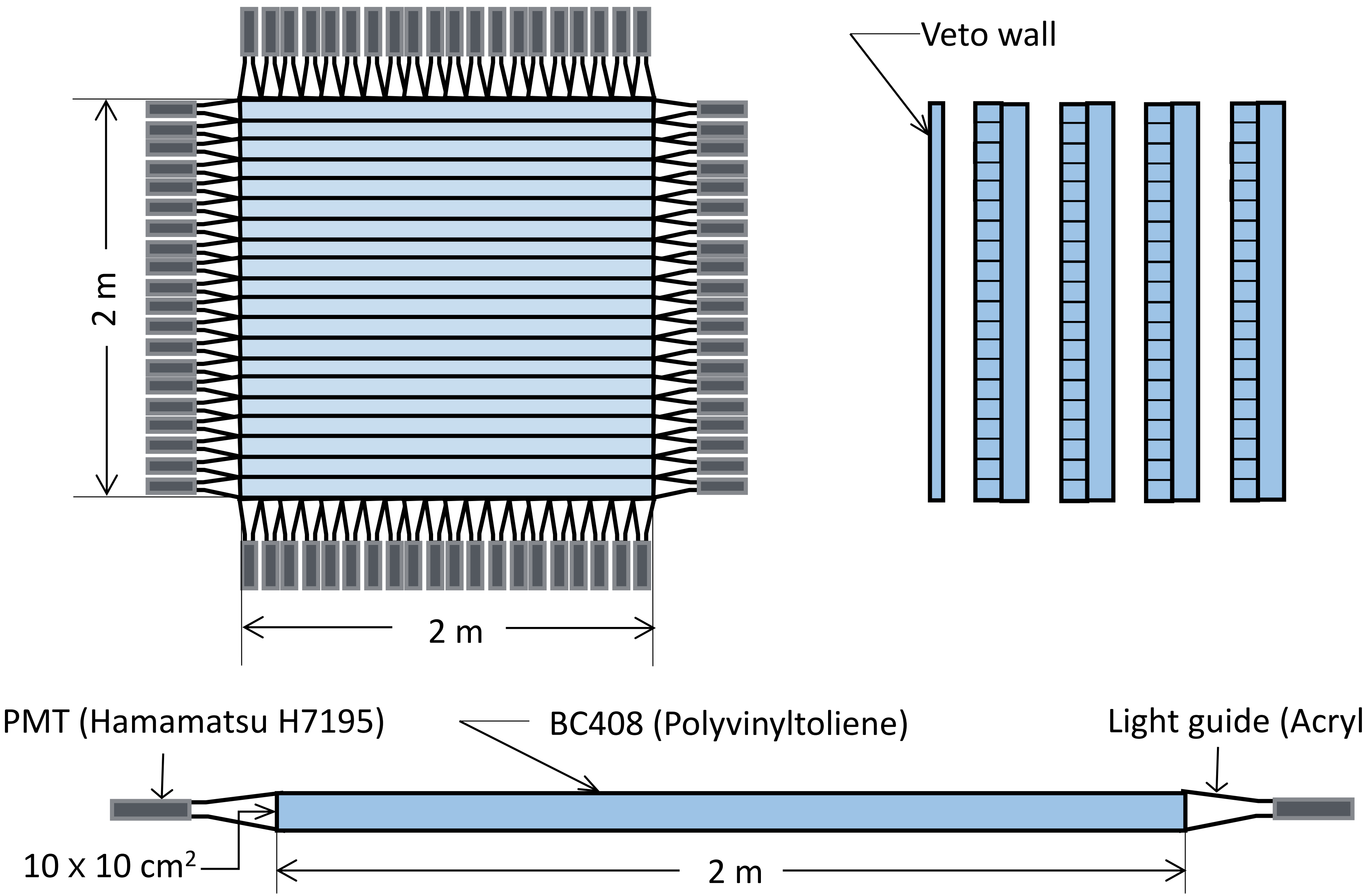


- Pad dim.: ~ 3×10 mm^2
- # of Ch.: 2,618/sector × 8 sectors = 20,944
- FEE: 11 AsAD/sector × 8 sectors = 88 AsAD



- Final design of readout, gas vessel, and field cage is in progress.
  – Readout will be only at the upstream endcap.
  – P20 with v_{drift} > 6 cm/μs covers entire readout time of GET over full drift length
  – Inner radius: 150 →100 mm, Outer radius: 500 →535 mm
  – Maximize the active region for R = 105~503.5 mm
- Test of the real-size GEM foil is underway.
  – If gain is too small, the quadruple GEM configuration will be tested.
- LAMPS TPC will be constructed in 2019-2020 and tested by 2021.

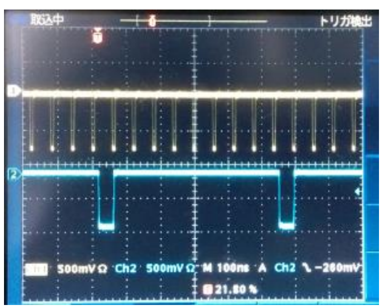
Neutron detector array

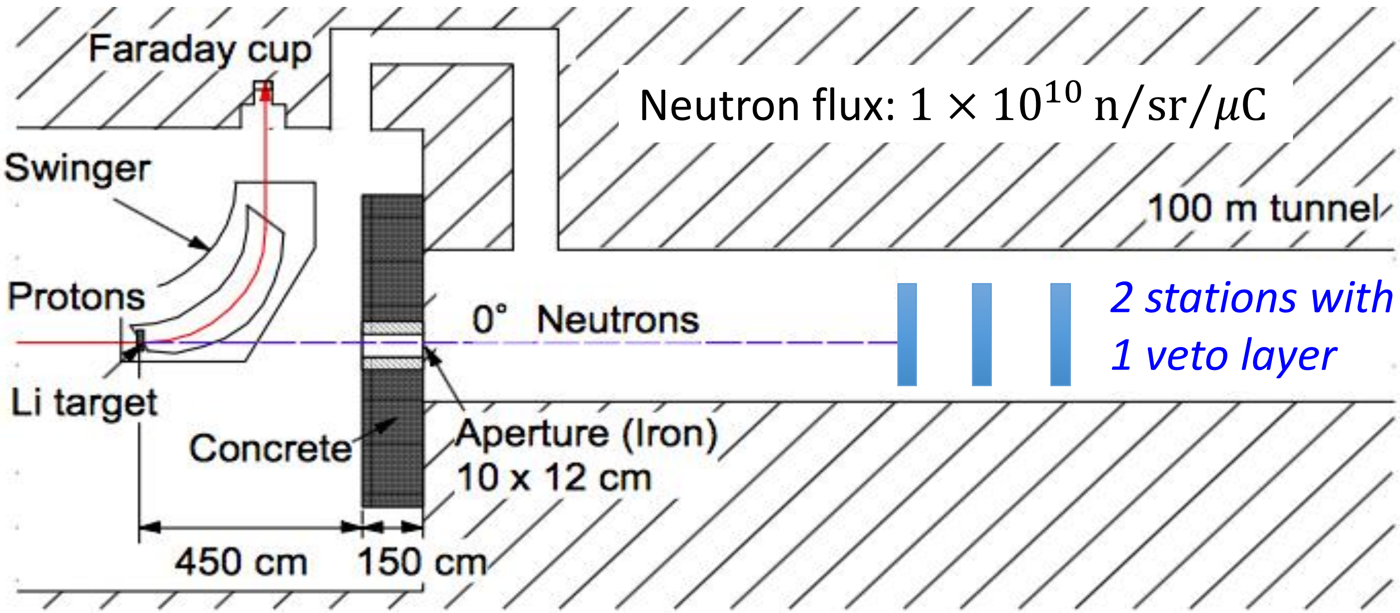


Neutron detector: Beam test at RCNP

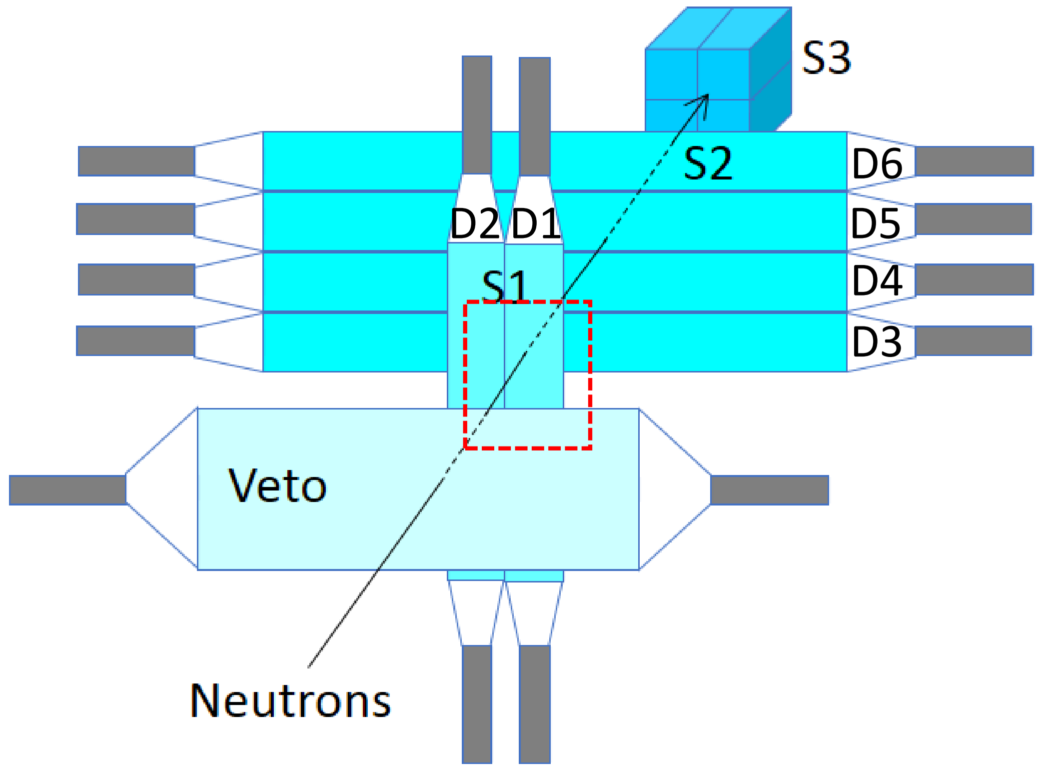
- E479 approved in B-PAC in March 2016
- Date: May 2016
- Beam specifications
  - Protons on Li production target (p+^{7}Li → n + ^{7}Be)
  - Neutron energies: 65 and 392 MeV in N0 beamline
  - 10 nA flux × 1/9 chopping
  - Background neutron above 3 MeV is less than 1% [NIMA629, 43 (2011)]

Chopping signals



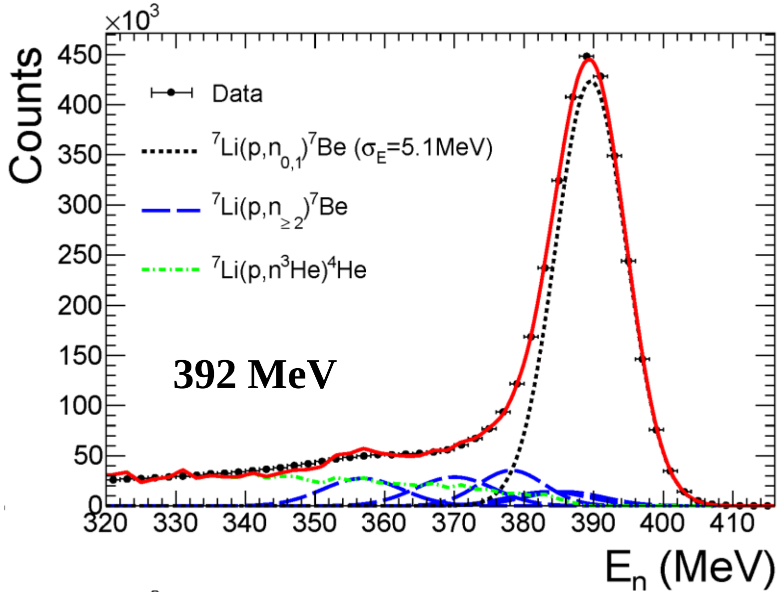


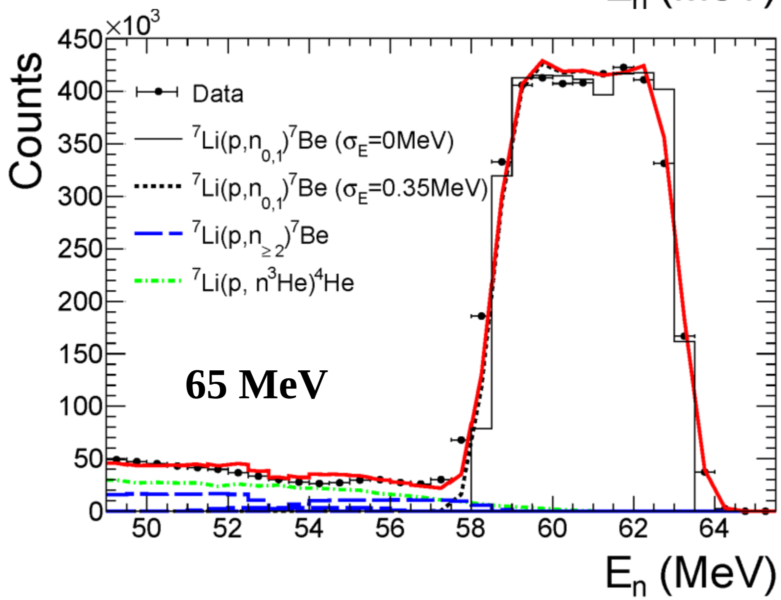
Neutron detector: Beam test at RCNP



- Distance from target to the detector: 15 m
- Gap between stations: 60 cm
- Dim. of each S1 detector: $10 \times 10 \times 100$ cm^3
- Dim. of each S2 detector: $10 \times 10 \times 200$ cm^3
- Beam size at S1: 25×30 cm^2

Neutron detector: Energy resolution



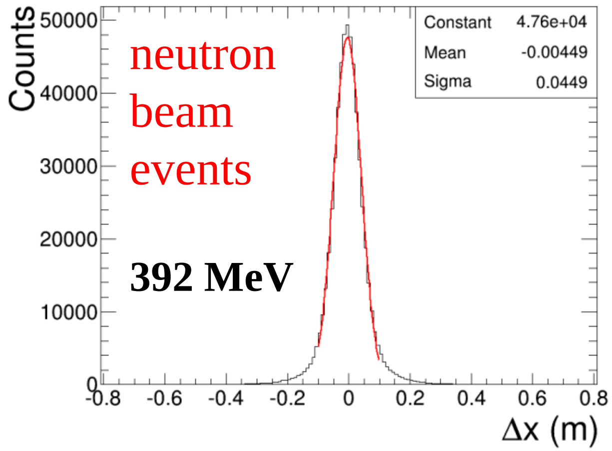


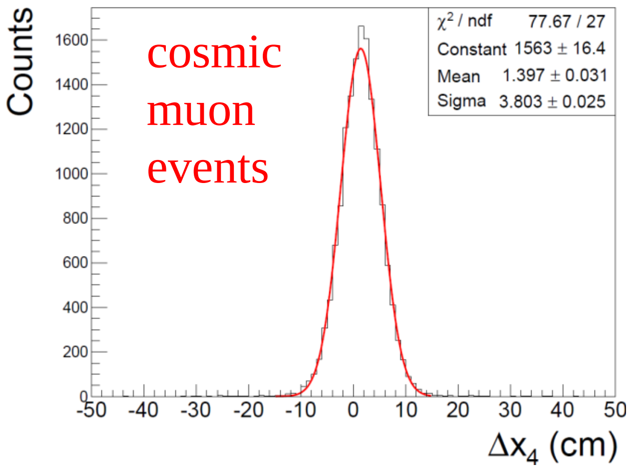
^{7}Be

E^* [keV]	$2J^\pi$	E_α [keV]	$\sigma\ (\alpha,\gamma)$ mbarn	ω_γ [meV]	$T_{1/2}$ or Γ_{cm}
0.0*	3^-				53.22(6) d
429.08(10)*	1^-				133(17) fs
4570(50)	7^-	3000(30)	7.9(5)	330(210)	210(10) keV
6730(100)	5^-				1.2 MeV
7210(60)	5^-				0.40(5) MeV
9270(100)	7^-				
9900	3^-				≈1.8 MeV
11010(30)	3^-				320(30) keV
17000	1^-				≈6.5 MeV

- Large energy loss in Li target at 65 MeV
- Low-energy background dominated by the 3-body decays $^{7}\mathrm{Li}(p,n\ ^{3}\mathrm{He})\ ^{4}\mathrm{He}$
- Energy resolution (FWHM):
  - 3.1% @ 392 MeV
    ⇔ 3.4% without background subtraction
  - 1.3% @ 65 MeV

Neutron detector: Position resolution





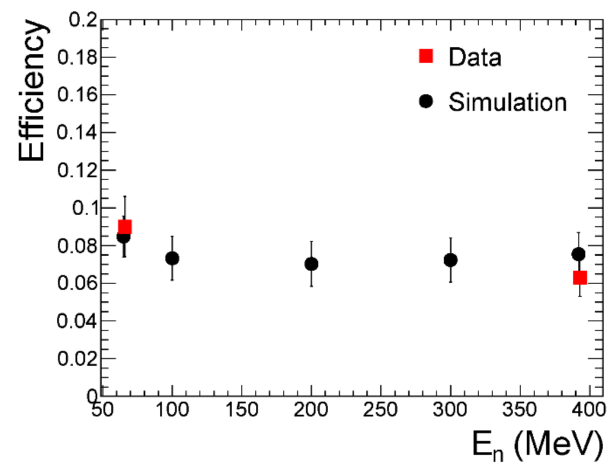
- Hit position difference between $D1$ and $D2$ for neutrons with simultaneous hits: $\Delta x_{S1} \equiv x_{D1} - x_{D2}$ for 10 MeV threshold and $\delta t < 3$ ns
- Relative position resolution for neutrons for one bar:

$$\sigma_n = \frac{\sigma(\Delta x_{S1})}{\sqrt{2}} = 4.5\text{ cm: } R_x(n) = 7.5\text{ cm (FWHM)}$$

- Position difference between the projected and hit positions for cosmic muons: $\Delta x_4 \equiv x_{D4,proj} - x_{D4,hit}$
- Relative position resolution for cosmics for one bar:

$$\sigma_x = \frac{\sigma(\Delta x_4)}{1.87} = 2.0\text{ cm: } R_x(\mu) = 4.8\text{ cm (FWHM)}$$

- Single-bar detection efficiency: Experimental data agree with the simulation results.



Neutron detector: Performance

Characteristics of prototype LAMPS neutron detectors

Data	Cosmic muons	Neutron beams at 65 MeV	Neutron beams at 392 MeV
Time resolution (ps)	309		
Position resolution (cm)	4.8	7.6	7.5
Energy resolution (%)		1.3	3.1
Efficiency (%)		9.0 ± 1.6	6.3 ± 1.0

Comparison of performance for similar kind of neutron detectors

	LAMPS (this work)	MoNA [13]	NEBULAR [14]	LAND [15]
Dimensions (cm^3)	$10 \times 10 \times 200$	$10 \times 10 \times 200$	$12 \times 12 \times 180$	$10 \times 10 \times 200$
Time resolution (ps)	309	423	376	588
Position resolution (cm)	4.8	5.2	6.1	7.1

[13] William Alexander Peters, Study of neutron unbound states using the modular neutron array (MoNA) (Ph.D. thesis), Michigan State University, 2007.

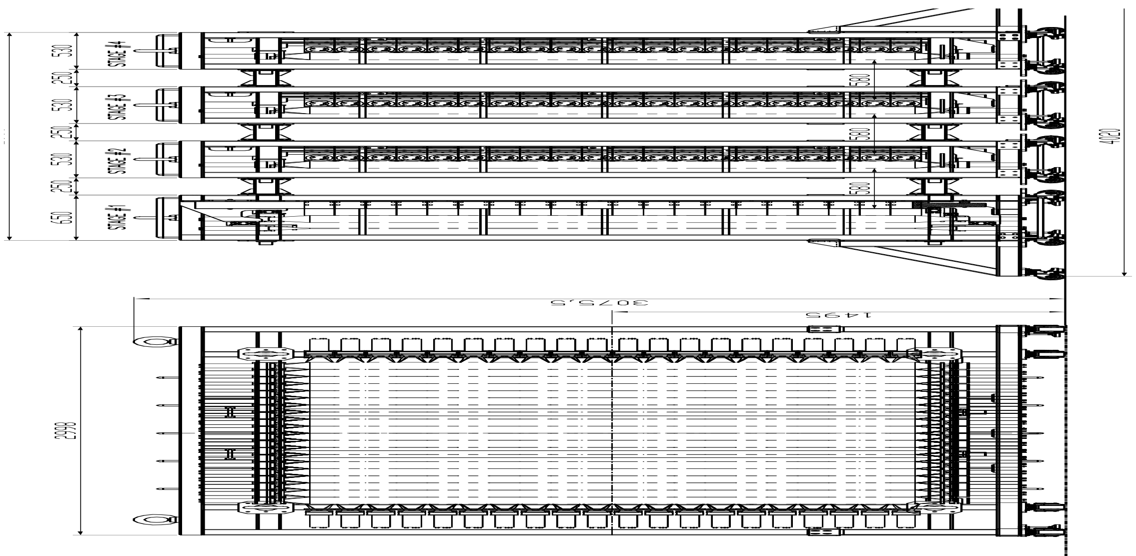
[14] Y. Kondo, https://indico2.riken.jp/event/407/contributions/9052/attachments/5776/6707/SAMURAI-intWS-NEBULA-web.pdf.

[15] O. Yordanov, et al., Nucl. Instrum. Methods B 240 (2005) 863.

H.H. Shim et al., NIMA 927, 280 (2019)

Rare Isotope Science Project

Neutron detector: Frame

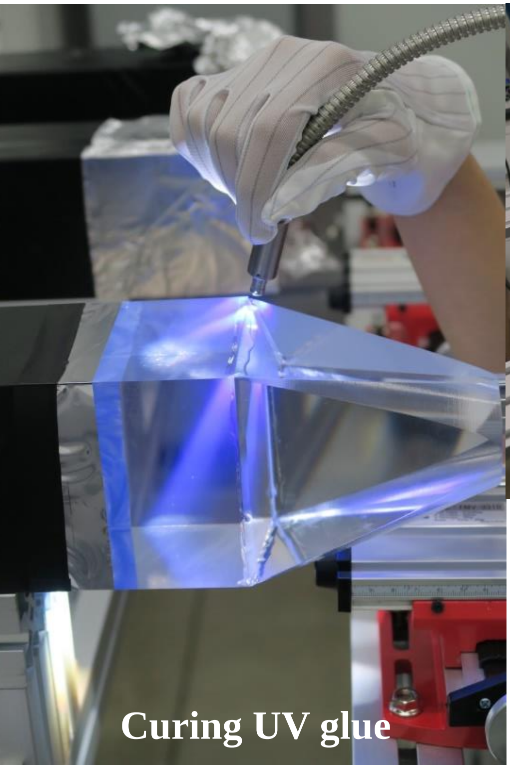


Light-tight PMT clamps

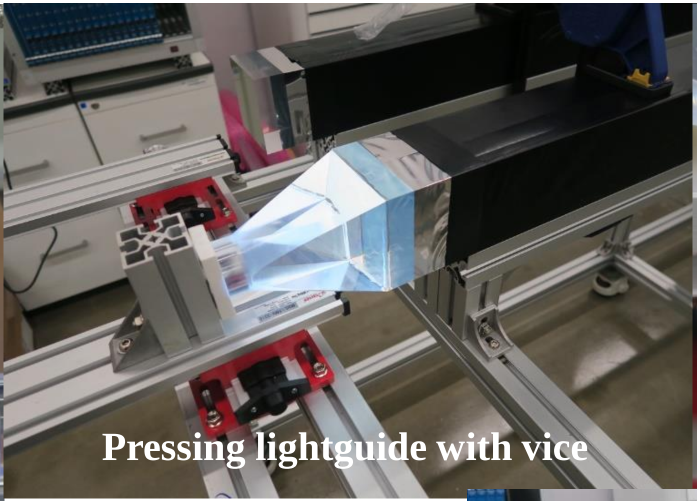
Array frame

Module fixture

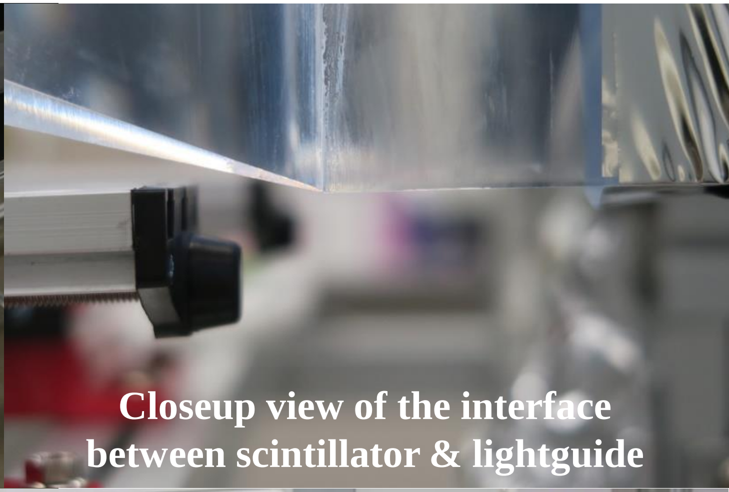
Neutron detector: Module preparation



Curing UV glue



Pressing lightguide with vice



Closeup view of the interface between scintillator & lightguide

Waiting for hardening glue

Detector modules, sorted by PMT gains, are waiting for final assembly on the frame.

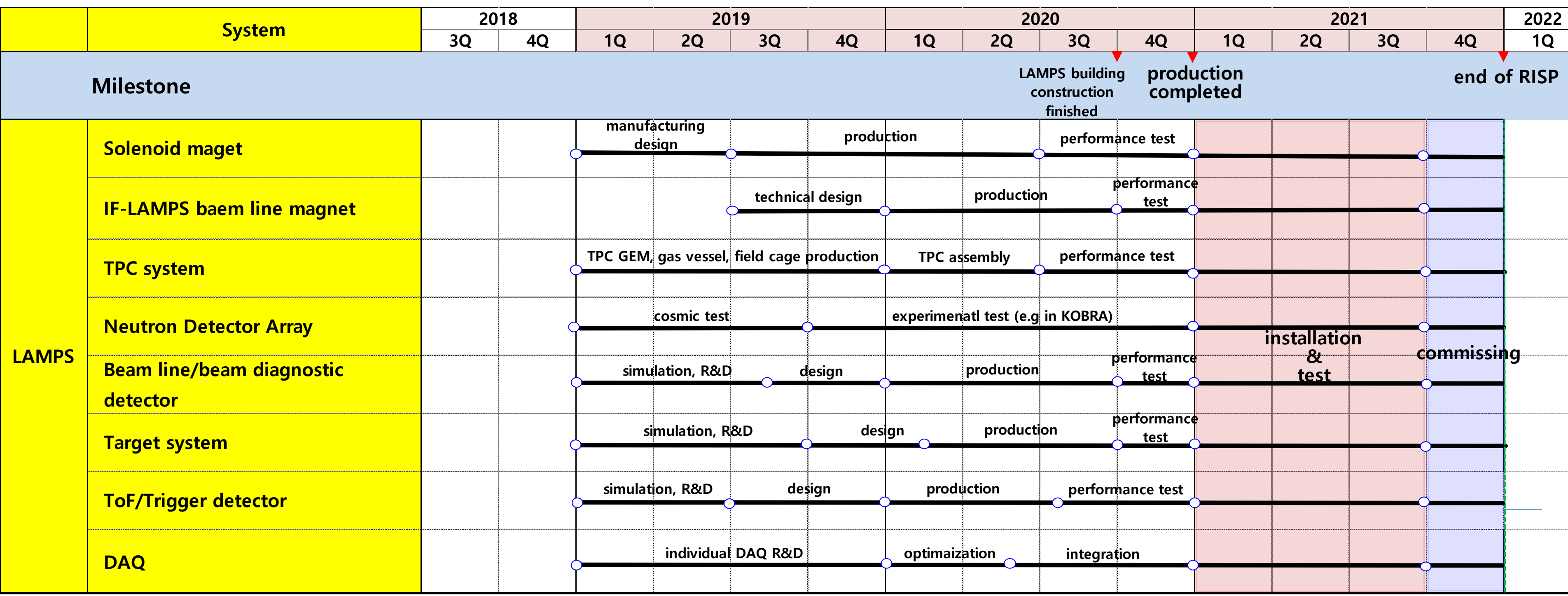
Neutron detector: Assembly

- Installation of all modules (160 detectors + 20 vetos) in the frame was completed at the Sejong campus Lab. of Korea University in Dec. 28, 2018.
- Cosmic muon test just started.
- Detector operation can be remotely done in Seoul.

Status of the LAMPS Collaboration

- RISP/IBS: **Young Jin Kim**, Hyo Sang Lee, Min Sang Ryu
- Korea University: Jung Keun Ahn, **Byungsik Hong**, Young Seub Jang, Jiseok Kim, Minho Kim, Jong-won Lee, Jaehwan Lee, Jung Woo Lee, Kyong Sei Lee, Byul Moon, Benard Mulilo, Seon Ho Nam, Jaebeom Park, Jeonghyeok Park, Hyunha Shim
- Chonbuk Nat. University: **Eun-Joo Kim**
- Chonnam Nat. University: **Dong Ho Moon**, SeongHak Lee
- Inha University: **Min Jung Kweon**, Hyungjun Lee
- Sejong University: **Yongsun Kim**, Hyebin Song
- Jeju Nat. University: **Jong-Kwan Woo**
- KRISS: **Sanghoon Hwang**

- 6 Korean Universities and 2 Institutes
- 27 Collaborators including 7 Profs., 7 research staffs and 13 students
- Globalization is needed!
- Contact me at bhong@korea.ac.kr if you're interested in the project.



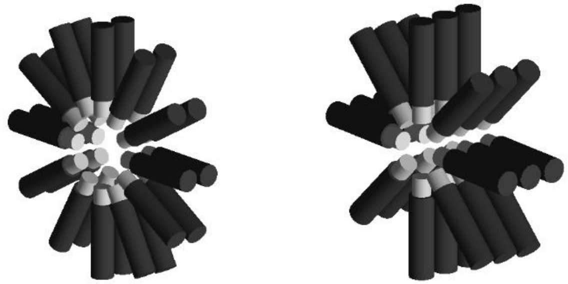
Revival on low-energy Expts. by LAMPS

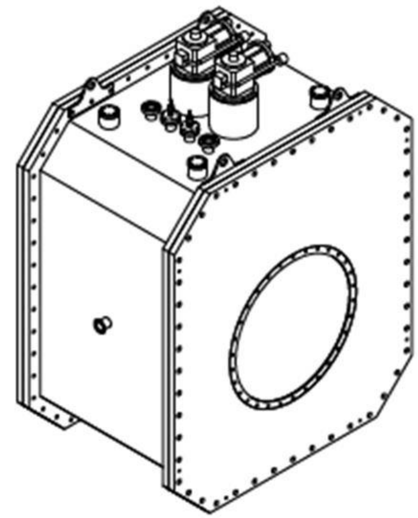
Center for Extreme Nuclear Matters (Director: B. Hong)
Supported by the National Research Foundation of Korea (NRF) via the "Science Research Center for Excellency" program from 2018 (Total 7 years and possible extension after evaluation)

- Three groups
  - Group 1 : High-energy heavy-ion collisions
  - Group 2 : Hadron physics
  - Group 3 : Radioactive ion beam physics
- Members
  - 9 professors, >15 postdocs & research staffs, >30 students
- Research center is independent of RISP/IBS, but …
  - Experimental professors in CENuM are very much interested in the low-energy experiments at RAON in early operational phase.
  - Therefore, CENuM started to develop some essential detector components for the low-energy nuclear experiments at RAON:
    - $LaBr_3$(Ce) gamma detector system
    - AT-TPC & Superconducting solenoid magnet
    - FAZIA type Si-CsI detector system

Revival on low-energy Expts. by LAMPS

- **$LaBr_3(Ce)$ gamma detector system**
  - Fast timing PMTs (R_t< 200 ps, R_E< 3.5%, ε~6.8% at 664 keV)
  - Total 24 modules (Plan to build 12 modules by 2020 and additional 12 by 2021)





- **AT-TPC & Superconducting solenoid magnet**
  - Superconducting solenoid magnet: 1.5 T, inner radius & length = 60 cm each
  - Magnet construction in 2019
  - AT-TPC construction by 2021

- **FAZIA Si-CsI detector**
  - Excellent isotope separated PID up to $Z \simeq 25$
  - Very useful for low-energy experiments at RAON

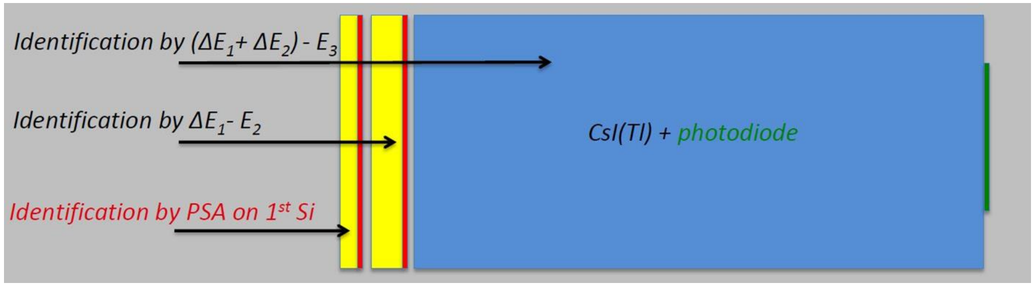


Figure borrowed from R. Bougault's presentation at IWND

Summary

- Rare Isotope Science Project (RISP) at IBS is the first large-scale nuclear physics project in Korea.
- The civil engineering, accelerator development, and detector construction for RAON have been aggressively progressed.
- LAMPS is a dedicated spectrometer for nuclear EoS and symmetry energy at RAON.
- Various components for LAMPS, including TPC, neutron detector array, magnet, are making a very good progress.
- Expect to finish the detector construction in about 2-3 years for nuclear experiments at early stage.