No ν Double-beta-decay Experiment

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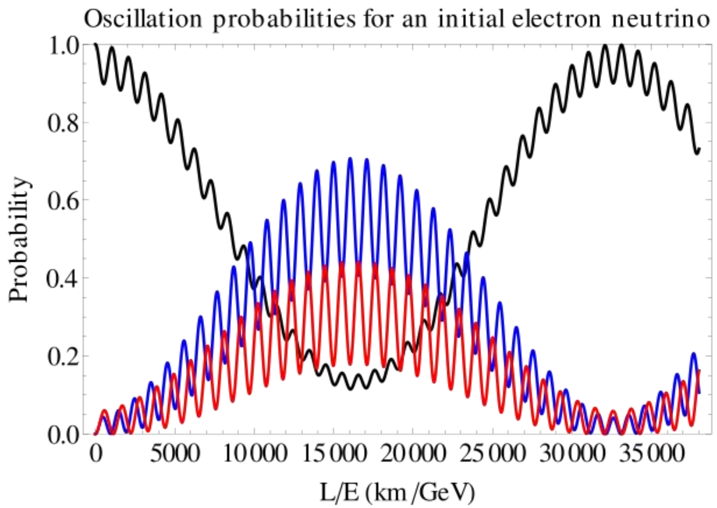
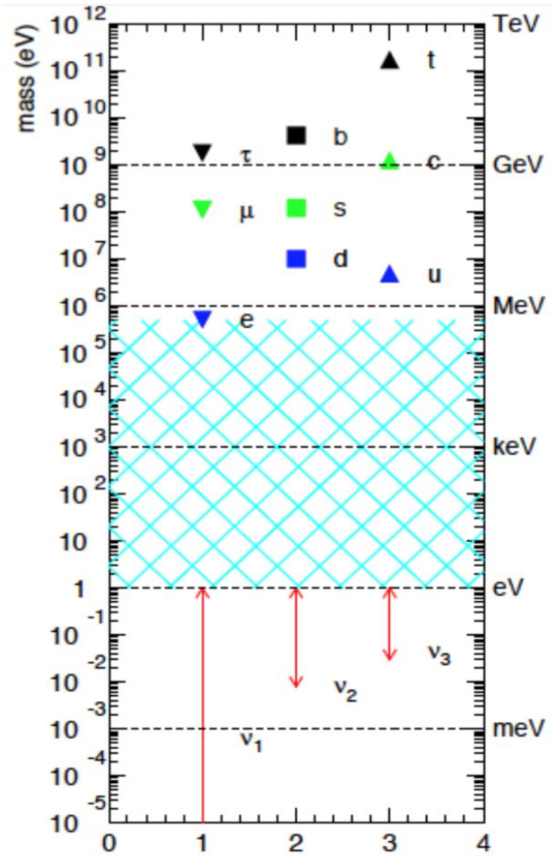
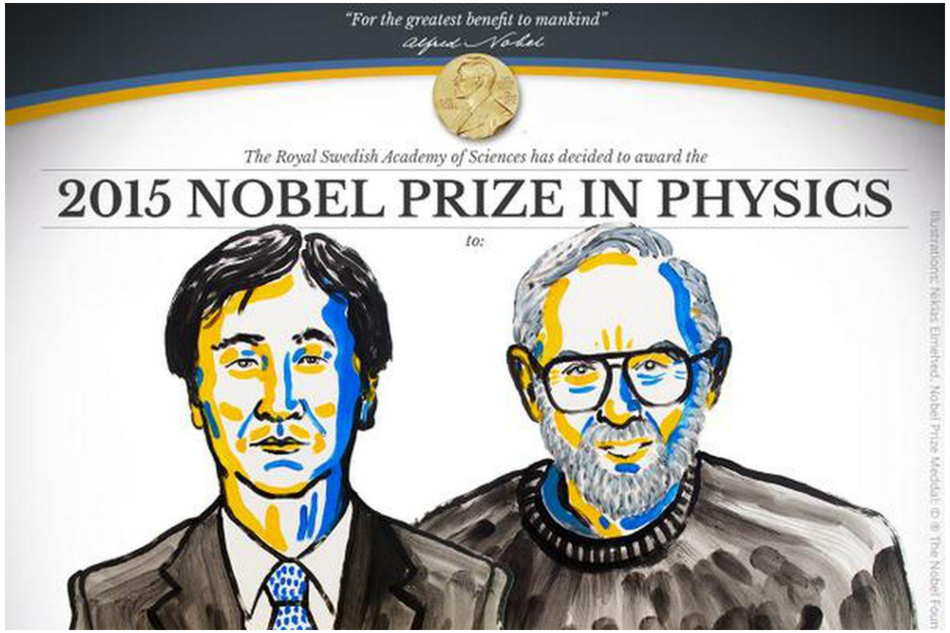
Neutrinos





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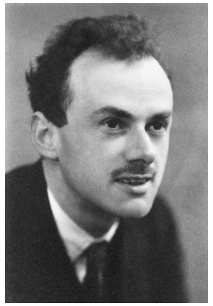
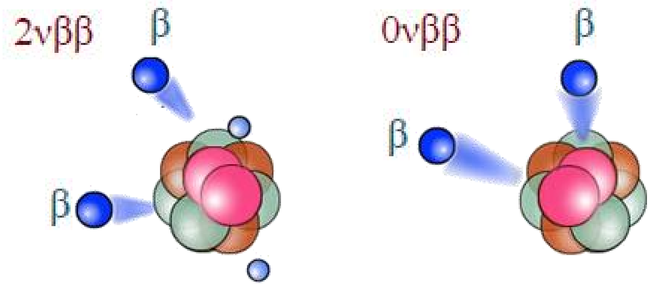
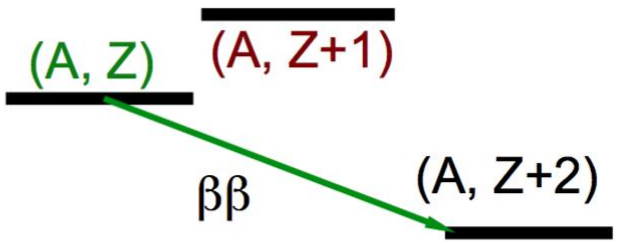

?

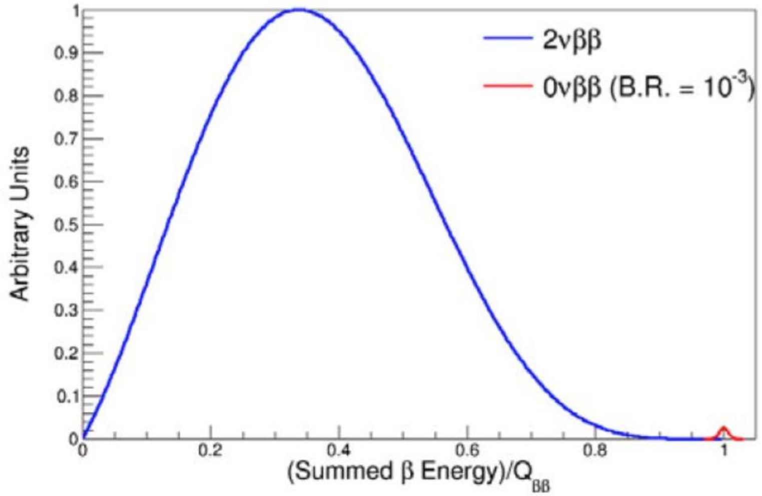
Super-Kamiokande, Super-K
Sudbury Neutrino Observatory, SNO

- Neutrinos oscillate ⇒ they have finite mass ⇒ beyond Standard Model
- Could be Majorana or Dirac fermions (could be their own anti-particle)
- Have "unnaturally" tiny mass

Neutrinoless Double Beta Decay (0νββ)







- Unstable nuclei may undergo ββ decay if single β-decay is energetically forbidden
- If 0νββ decay is observed, it
  - will prove that ν is a Majorana particle ⇒ beyond Standard Model
  - may explain the finite but tiny ν masses, by see-saw mechanism with an extended Standard Model
  - will constrain absolute ν mass, and ν mass hierarchy
  - may explain matter-antimatter asymmetry in the universe, since it violates CP symmetry and lepton number conservation

The experiments

- International experiments such as KamLAND-Zen, NEXT, CUORE, GERDA, are all operating at the hundred-kilogram scale.

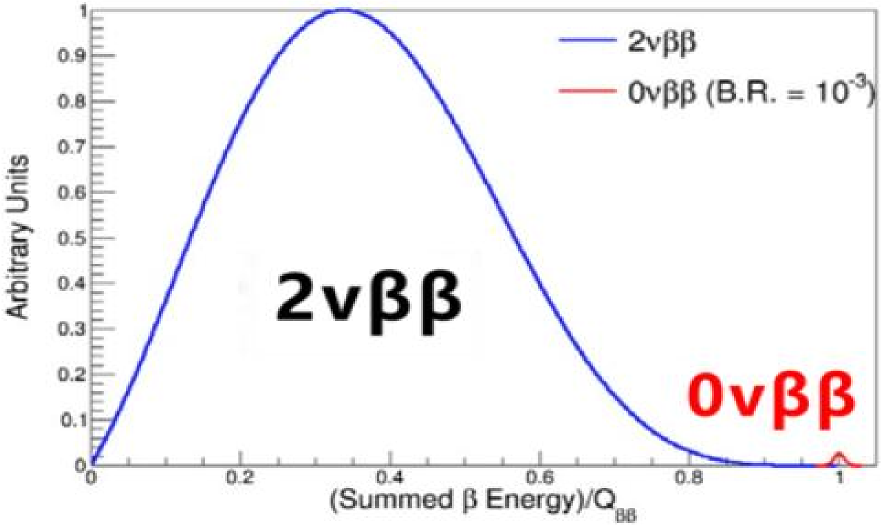
- Experiments in China: CDEX, PandaX, CUPID-CJPL, NvDEX, and JUNO, etc.

0νββ Experimental Methdology

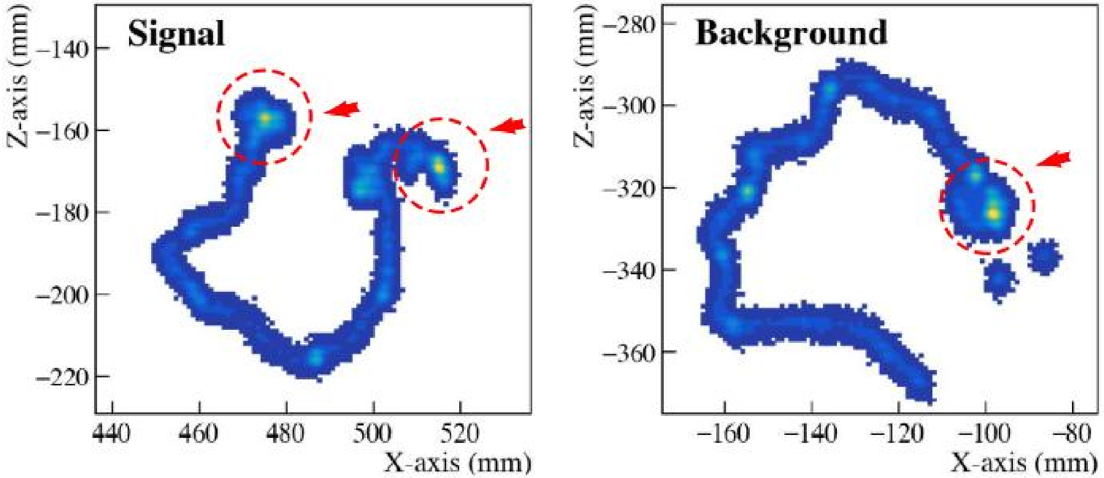
- The search for 0νββ relies on special isotopes that can potentially exhibit this rare nuclear decay process.

- Build a experiment, measures it, and confirm it.

Isotope	$Q_{\beta\beta}$ (KeV)	Natural abundance (%)	2νββ Half-life (10^{21}year)
$^{76}Ge \rightarrow ^{76}Se$	2039	7.8	1.926
$^{130}Te \rightarrow ^{130}Xe$	2528	34.5	0.820
$^{136}Xe \rightarrow ^{136}Ba$	2479	8.9	2.165
$^{48}Ca \rightarrow ^{48}Ti$	4271	0.187	0.064
$^{82}Se \rightarrow ^{82}Kr$	2995	9.2	0.096
$^{96}Zr \rightarrow ^{96}Mo$	3350	2.8	0.024
$^{100}Mo \rightarrow ^{100}Ru$	3034	9.6	0.007
$^{150}Nd \rightarrow ^{150}Sm$	3367	5.6	0.009



- ☐ the total energy of the two electrons is expected to be at the decay Q-value

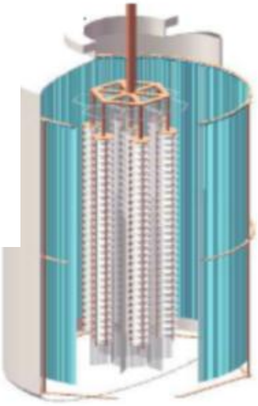
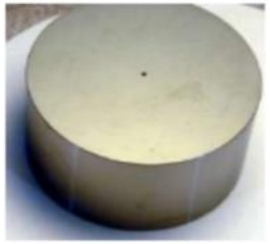


- ☐ Trajectory: two energy loss Bragg peaks at the end of the track

Main detector technology of 0νββ

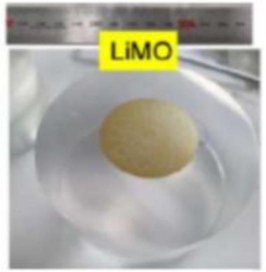
- The high-purity germanium (HPGe) detector（^{76}Ge）

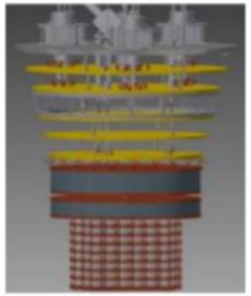
--- Gerda, Majorana, CDEX, LEGEND,.....

- Cryogenic Scintillating Bolometer ($Li^{100}MO$、$^{130}TeO_2$)

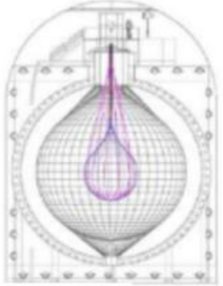
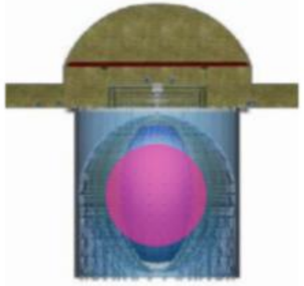
--- CUPID-CJPL, CUPID, CUORE, AMORE,......





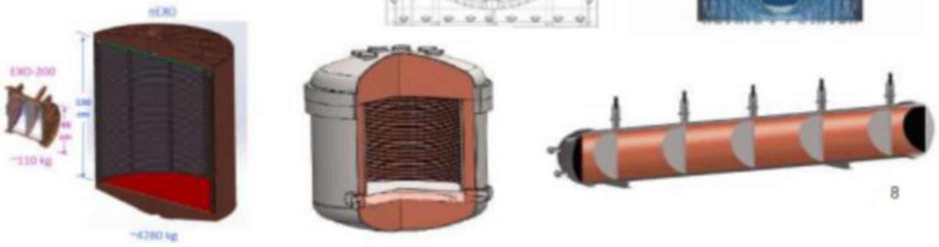
- Liquid scintillator（^{136}Xe、^{130}Te）

--- Kamland-Zen, SNO+, JUNO-0νββ,......

- Time Projection Chamber（^{136}Xe、^{82}Se）

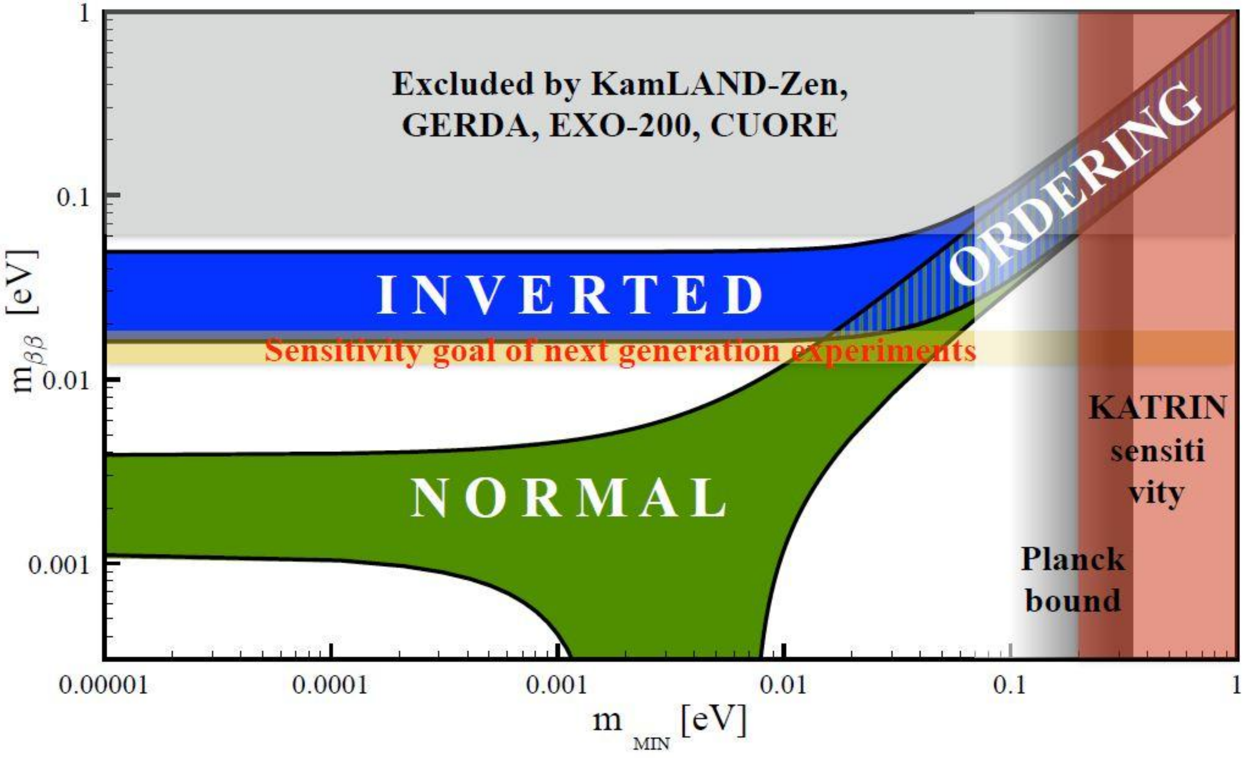
--- nEXO, NEXT、PandaX, NvDEx,.....

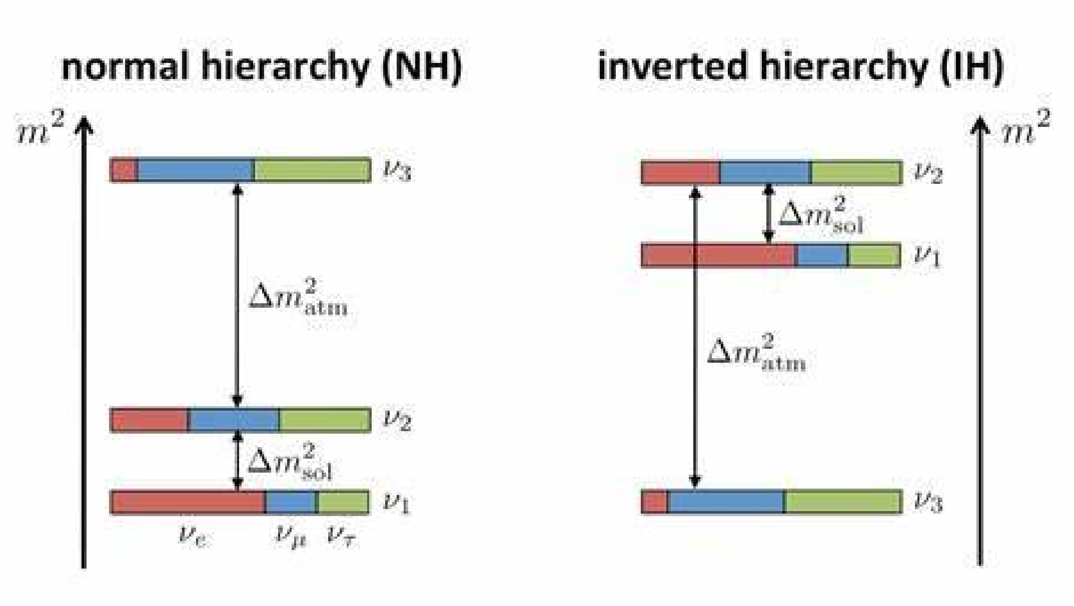


Main detector technology of 0νββ

	Isotope	^{82}Se	^{76}Ge	^{132}Te	^{136}Xe
1	**Method**	**Gas TPC**	**HPGe**	**Cryogenic Scintillating Bolometer**	**Liquid TPC**
2	E Resolution	~1%	< 0.5%	< 0.5%	> 2%
3	Q value (MeV)	2.996	2.047	2.528	2.479
4	Scalability	yes	no	no	yes
5	Surface background	no	yes	yes	no
6	Trajectory Measure	yes	no	no	yes

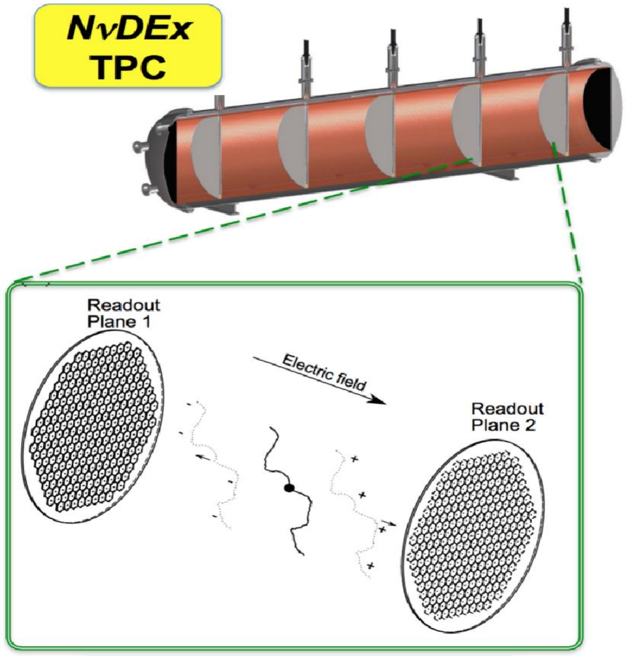
Status of 0νββ experiments

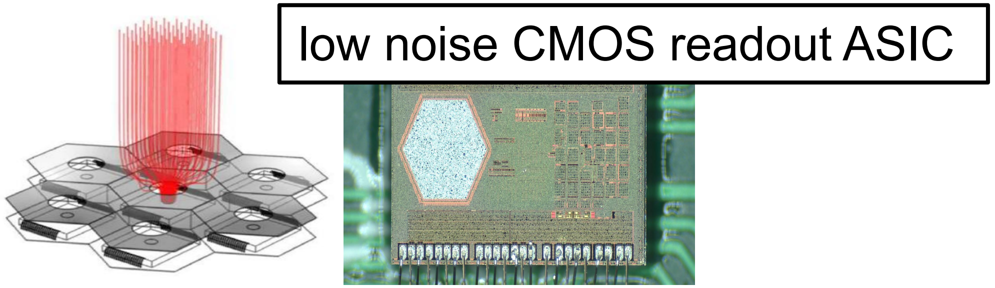


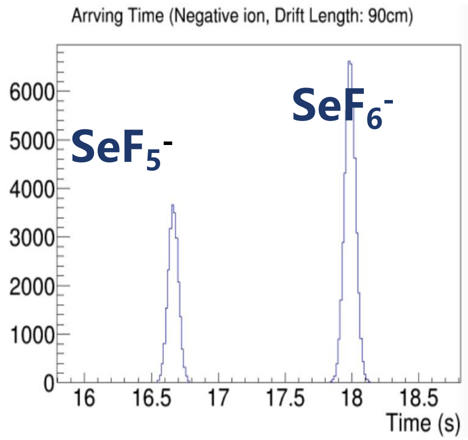


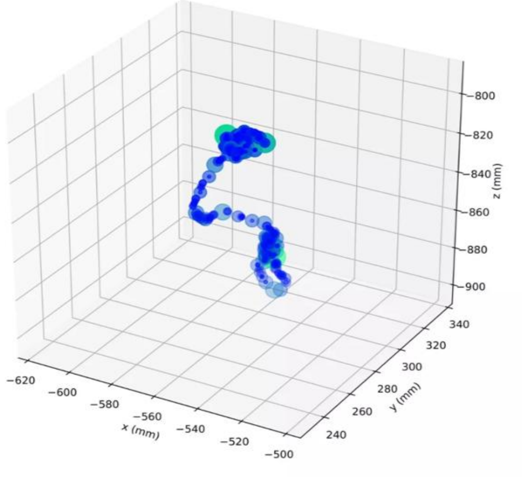
- Current leading experimental sensitivity: half-life sensitivity of 1.1×10^{26} years, and the upper limit for the $m_{\beta\beta}$ is 61-165 meV.
- The next generation of ton-scale experiments, cover the inverted hierarchy
- with half-life sensitivity of 10^{27}-10^{28} years, the upper limit for $m_{\beta\beta}$ of 10-50 meV.

NνDEx - No ν Double-beta-decay Experiment









- **High Pressure TPC with $^{82}SeF_6$**
  - Se undergoes 0νββ or 2νββ decay
  - Emits two electrons that ionize the gas.
  - Forms various SeFn± ions with SeF6 molecules
  - Drift towards the readout plane under the influence of an electric field.

- **Low noise Readout Plan without amplication**
  - Measure the arrvial time of $SeF_N^{\pm}$ ions
  - Measure the charges of ions

- **0νββ reconstruction**
  - Two bragg peaks at the end of the track
  - Total energy at Q value(2.996MeV)

Advantage of NνDEx

China JinPing Underground Laboratory，CJPL

Half Life sensitivity

$$T_{1/2}^{0\nu} \propto \varepsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \sigma}}$$

- Detector Efficiency (ε)
- Isotope abundance (A)
- Mass (M)
- Runing period (T)
- background (b)
- Energy Resolution (σ)

- High Q value of ^{82}Se (2.996 MeV) – above most natural radiation background
- Distinguish signal and background with event topology by TPC

➡ **Lower Background**

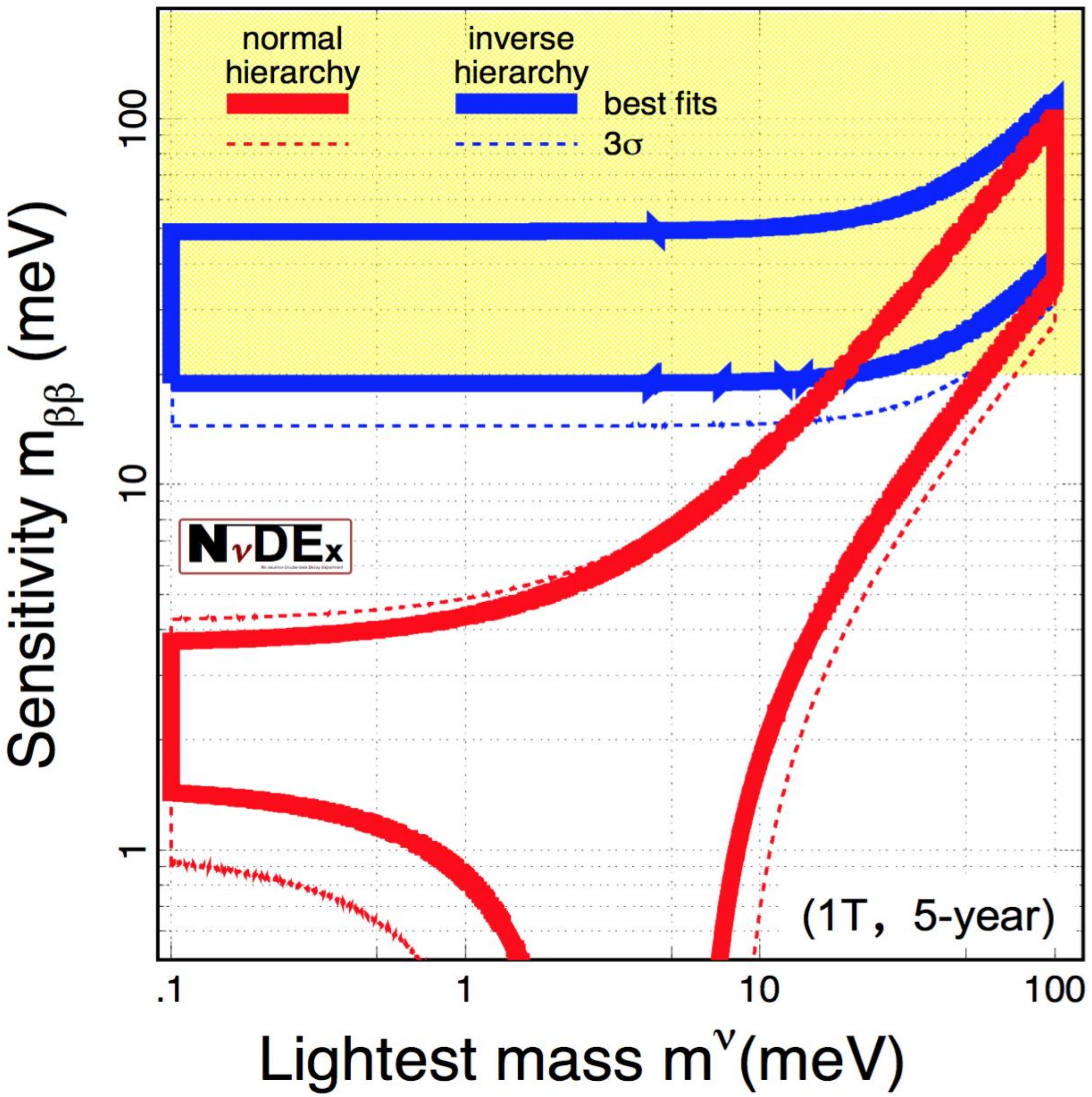
- Low noise CMOS ASIC (45e-) based readoutplane without avalanche amplification ➡ Energy resolution ~1% FWHM@Value

- Scalability of TPC to tons level without increasing surface noise ➡ **Increse Mass**

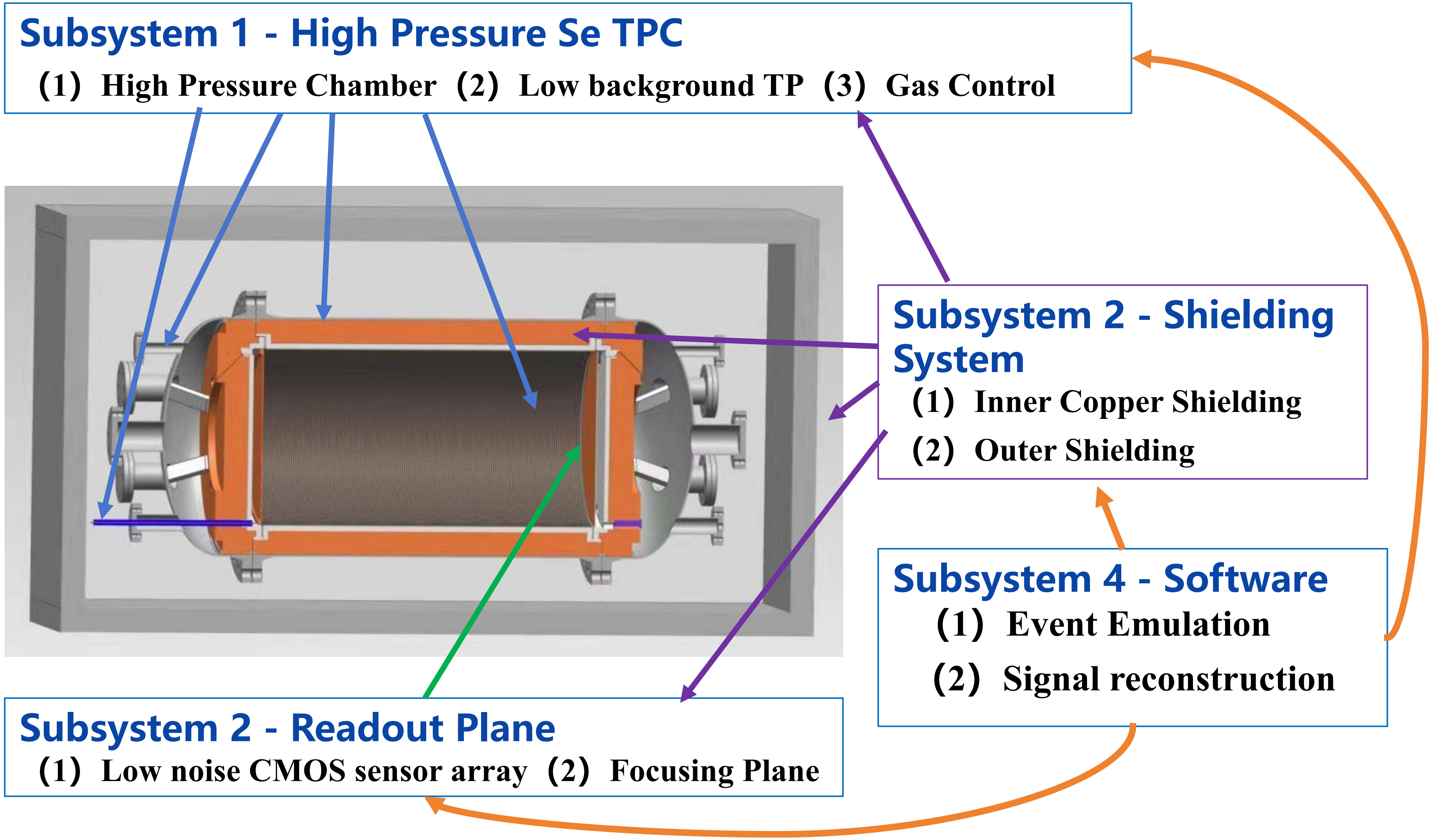
- **The first observation of 2νββ was made by TPC with Se**

NνDEx Overall Roadmap

- **Runing 100kg scale NvDEx experiments**
- 1-ton scale NvDEx experimental setup, 5-years operation, covering the inverted hierarchy.
- Expand the experimental scale without increasing additional background, reaching the normal hierarchy region.



NνDEx-100

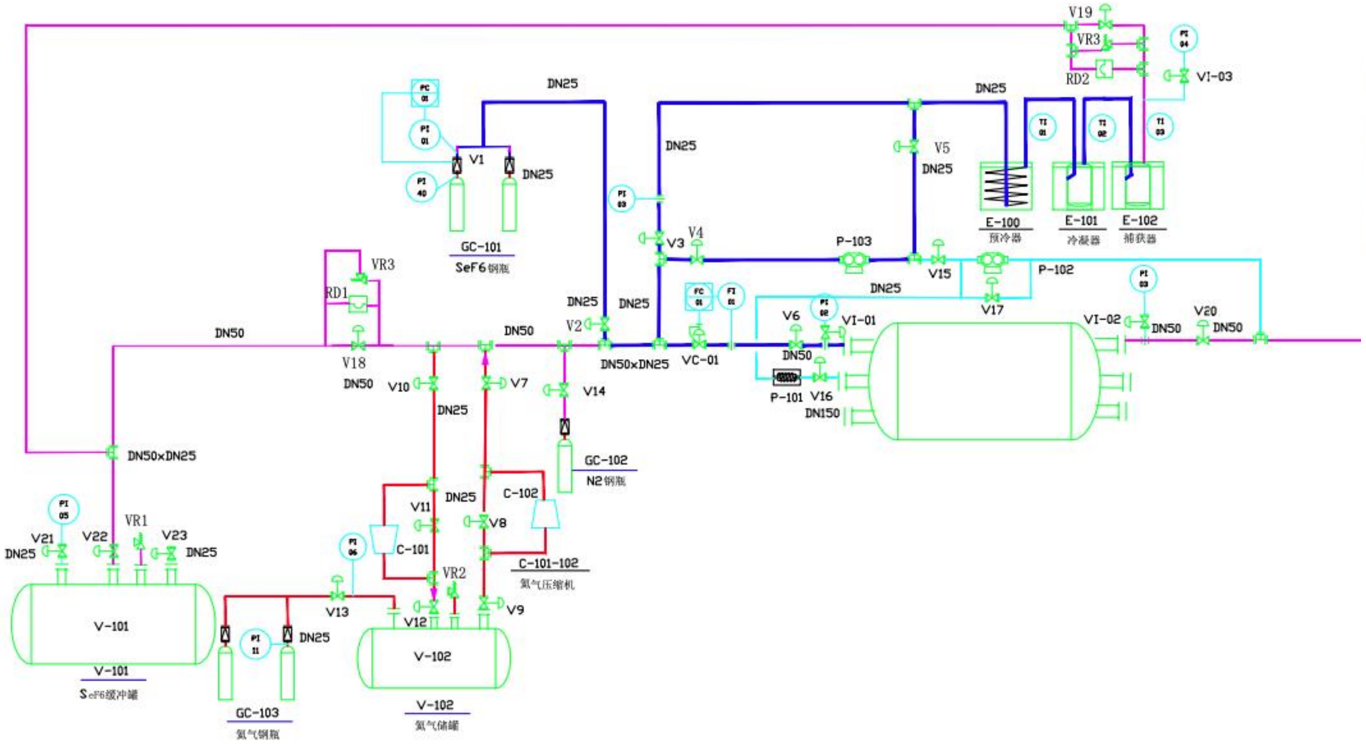


- NνDEx-100 is being built, with 100kg SeF_6 gas at 10 atm in the sensitive volume

High Pressure Chamber

- Weight ~2 ton
- Length： ~ 3.22 m
- Working volume： ~1.085 m^3
- Multiple Connecting Planes
  - DN50: Gas control
  - DN80: High Voltage
  - DN125: Low voltage, Fiber
  - DN150: Vaccum Control
- working at 10atm, max 15atm

Gas System & Gas Safety




pre-cooler


condenser


chiller

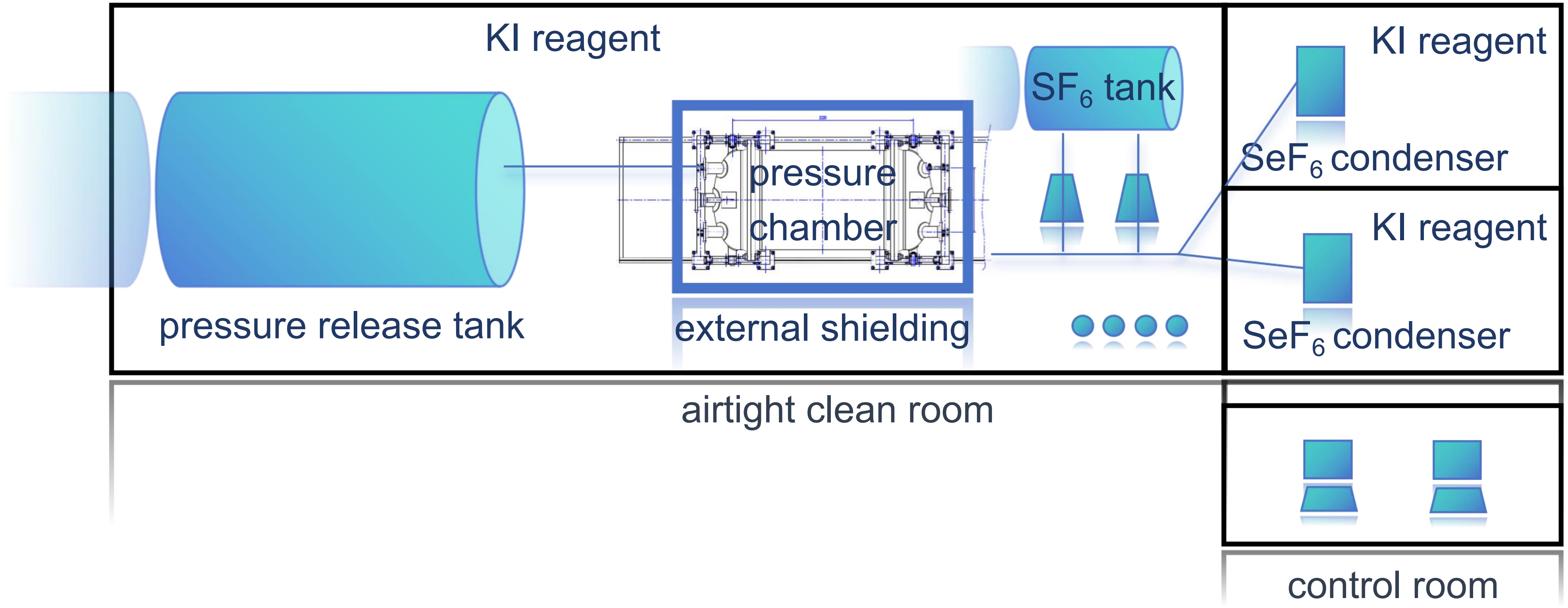

vacuum pump


emergent release tank


SF_6 storage tank

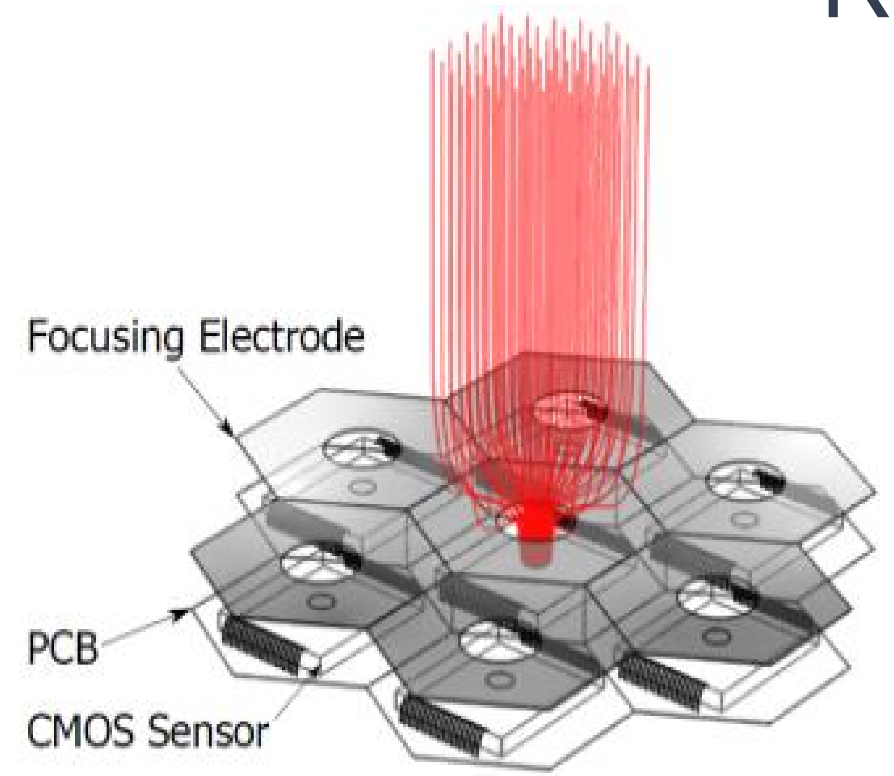
- SeF_6 is poisonous: < 0.05 ppm in environment ⇒ multi-layer safety measures
- A cold trap for SeF_6 storing
- An emergency tank for emergent SeF_6 releasing
- After SeF_6 is condensed and the system evacuated, a trace amount of residual gas is put into reactor containing potassium iodide (KI)
- Test with non-poisonous SF_6 for gas tightness before filling SeF_6 each time

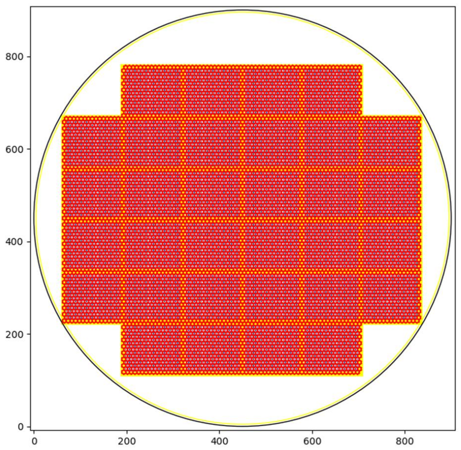
Airtight Clean Room

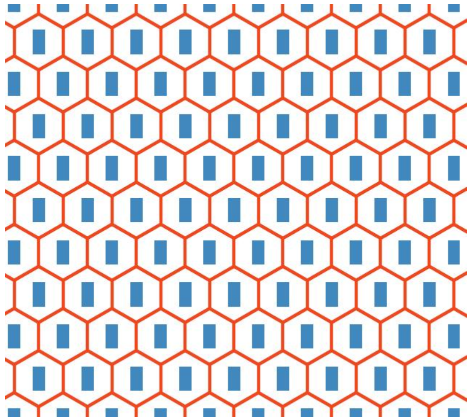


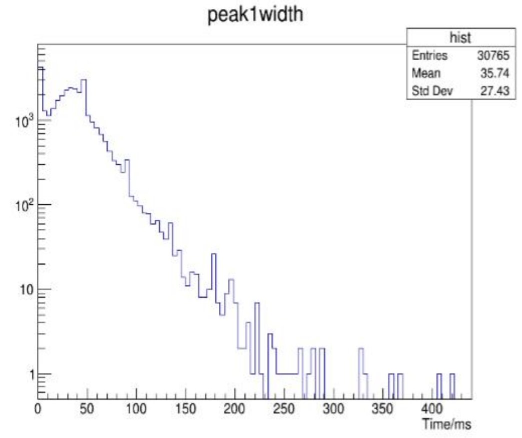
- The entire experimental set-up will be placed in an airtight clean room
- During data taking, the airtight clean room will be kept airtight, and the whole experiment will be controlled remotely
- Sufficient potassium iodide (KI) reagent placed to absorb SeF_6 in case of leakage
- When accessing the experiment, SeF_6 will be condensed in isolated airtight rooms

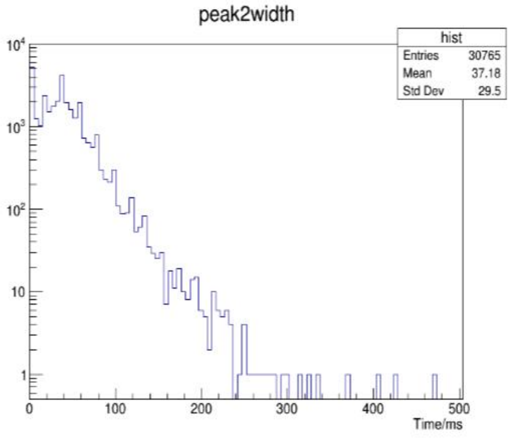
Readout Plane







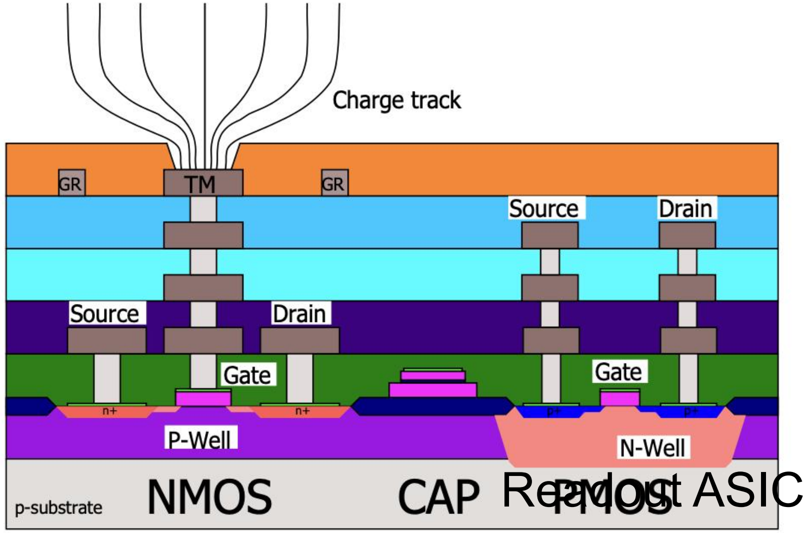


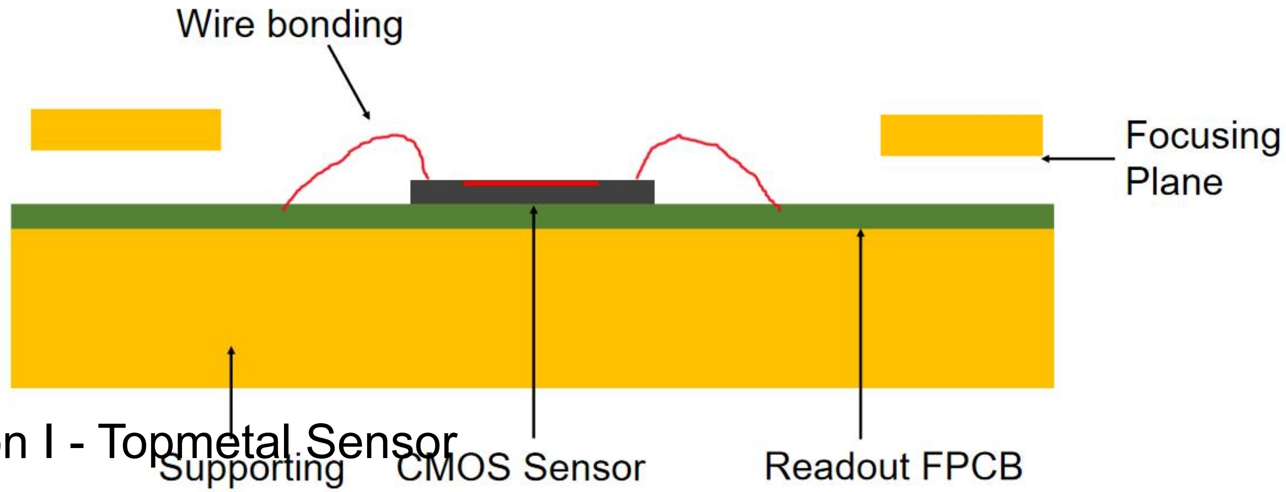


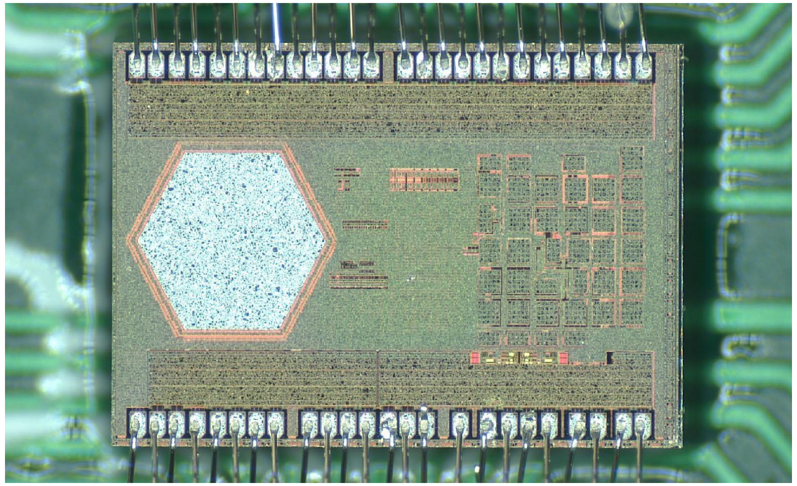
- ~15,000 low-noise CMOS ASIC chips (sensor) arranged in a hexagonal pattern
- The focusing plane ensure that all the ionization charges without amplication fall on the charge collection electrode
- Major Design specification of the ASIC
  - **input dynamic range > 40ke-,**
  - **equivalent noise charge < 45e-,**
  - **Integration continuously up to ~1s.**

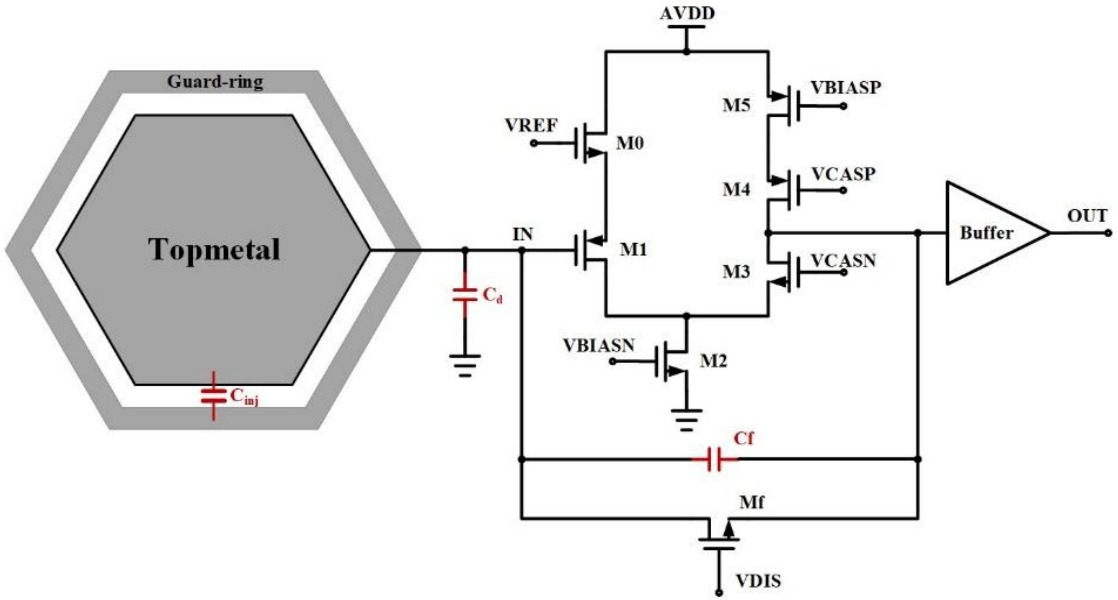
Readout ASIC Option I - Topmetal Sensor

Readout ASIC Option I - Topmetal Sensor

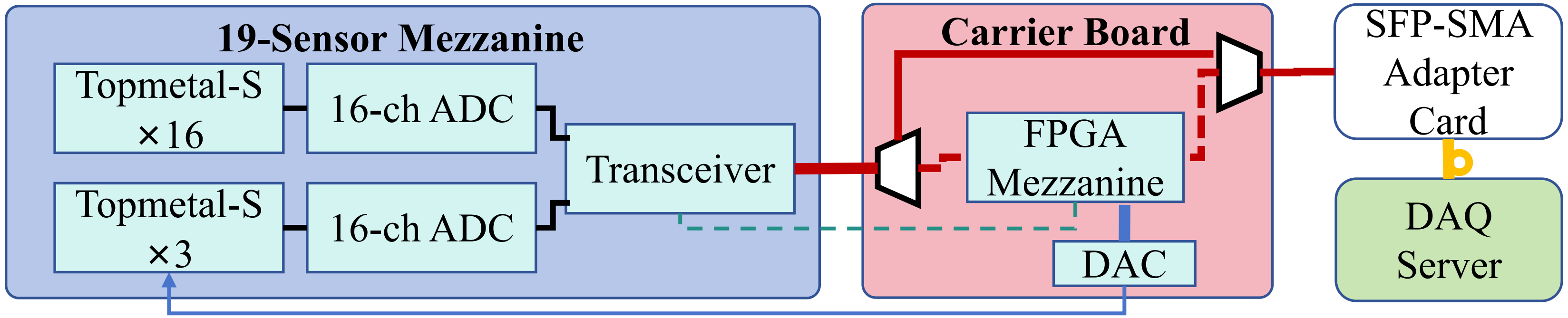


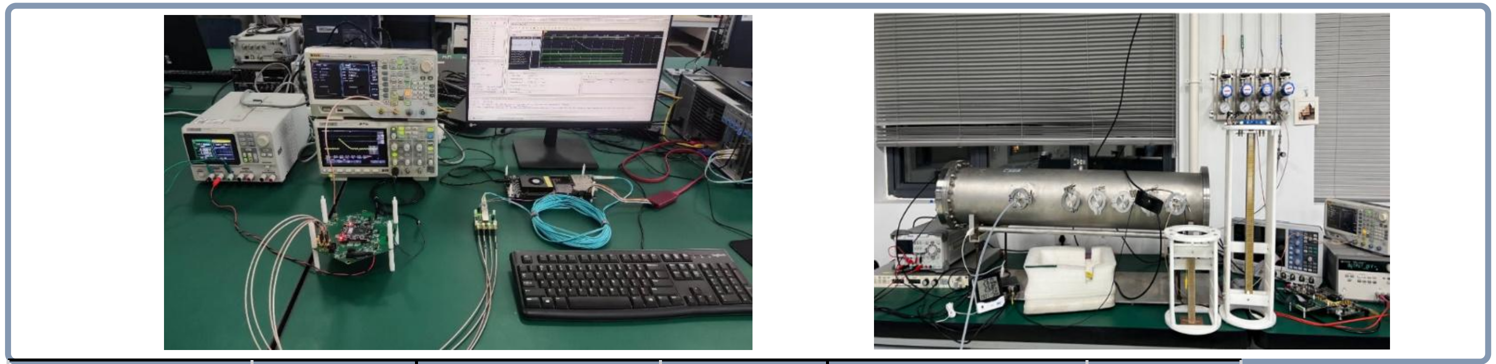


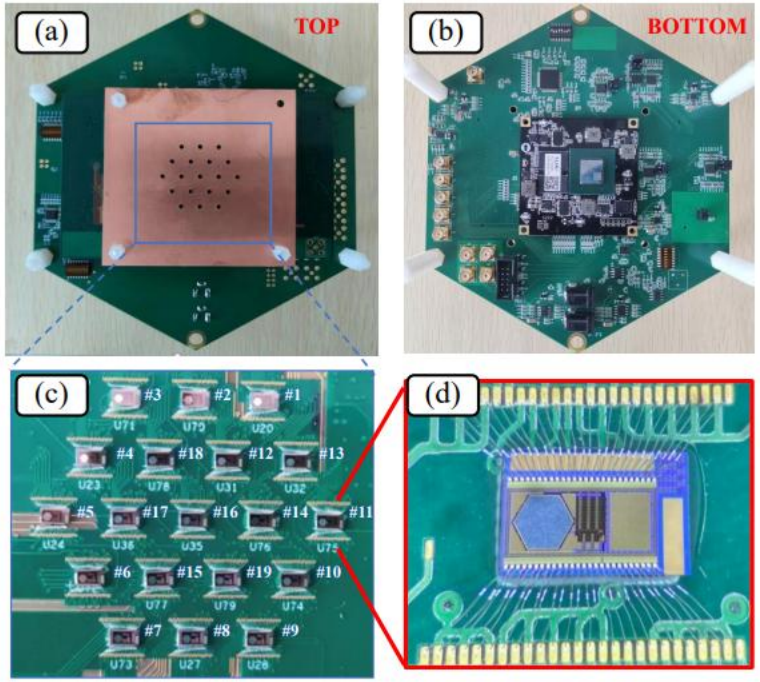




Readout ASIC Option I - Topmetal Sensor





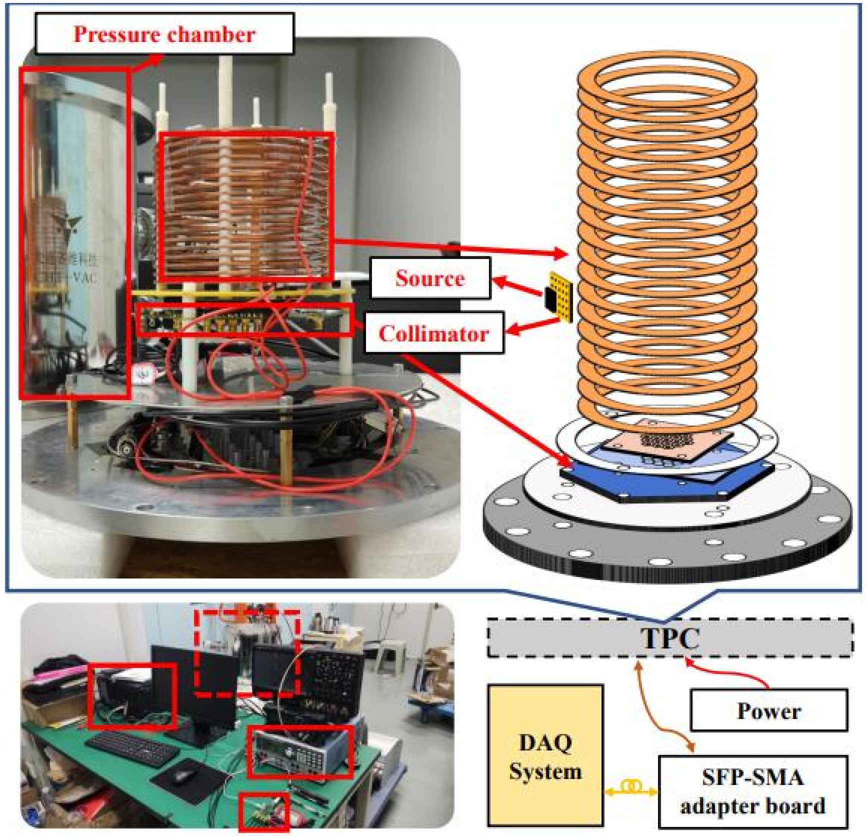


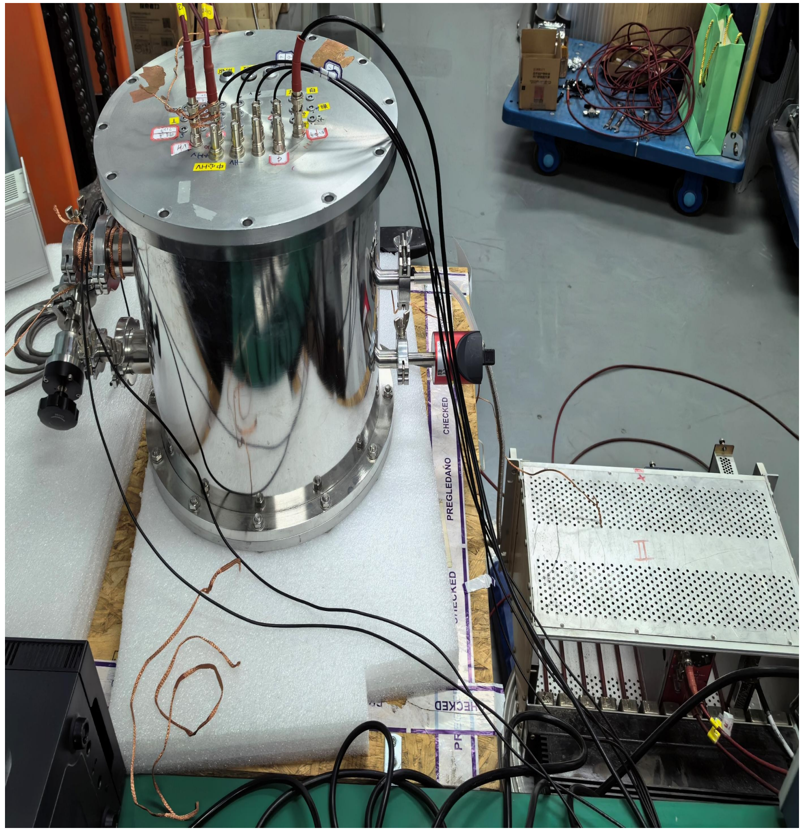
Topmetal-S ID	ENC(e^-)	Topmetal-S ID	ENC(e^-)	Topmetal-S ID	ENC(e^-)
1	141.526	8	104.058	15	110.072
2	139.486	9	110.927	16	114.208
3	127.576	10	-	17	115.762
4	128.232	11	133.518	18	132.716
5	118.966	12	137.611	19	102.677
6	109.841	13	136.486	-	
7	113.990	14	124.244	-	-

- Readout Plane with 19 Sensor
- The ENC is ~100 to 150 e-

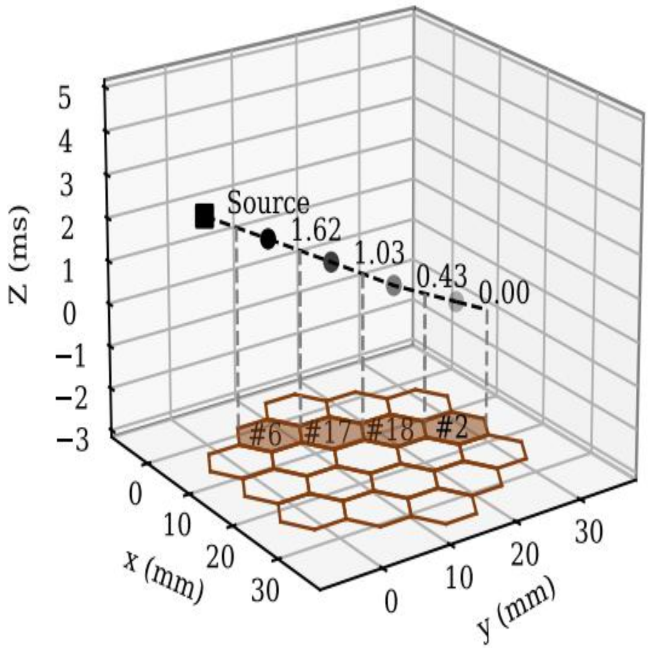
Readout ASIC Option I - Topmetal Sensor

- **Built a small scale sysmte for functional verfication**





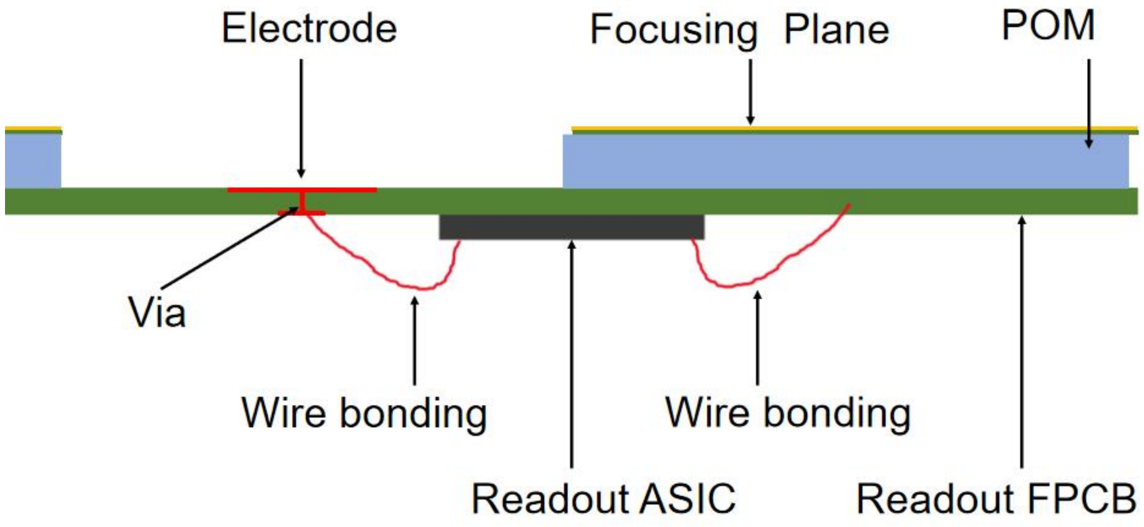
α track

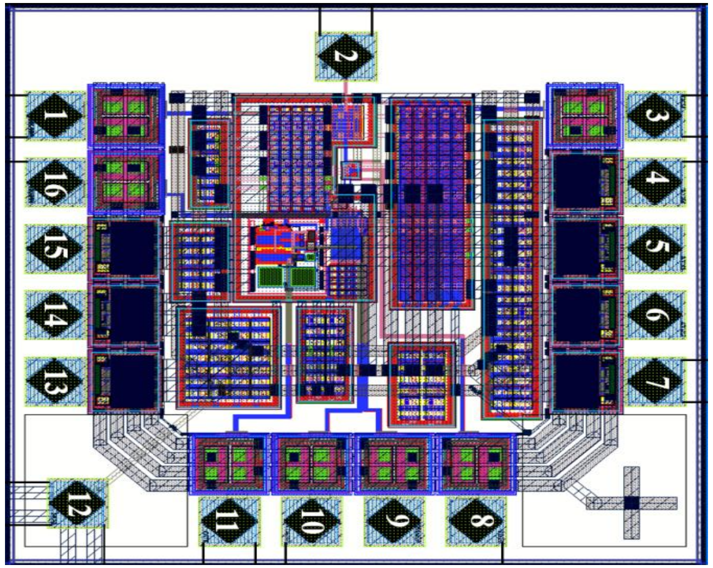


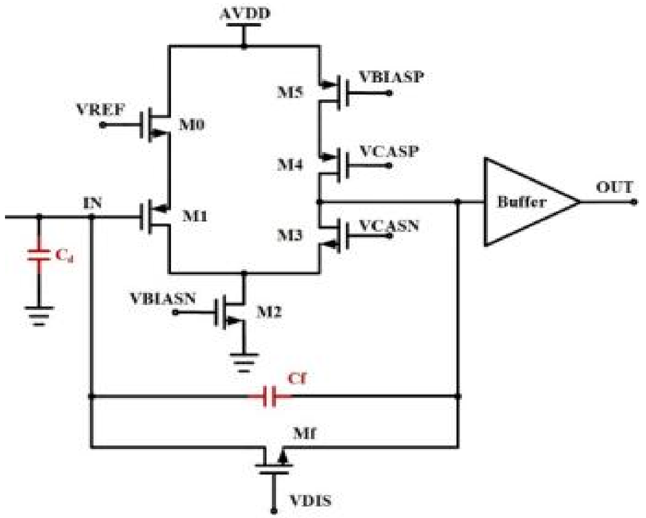
- The prototype system, including the TPC field cage, focusing plate, readout plane, and data acquisition system, is working properly.

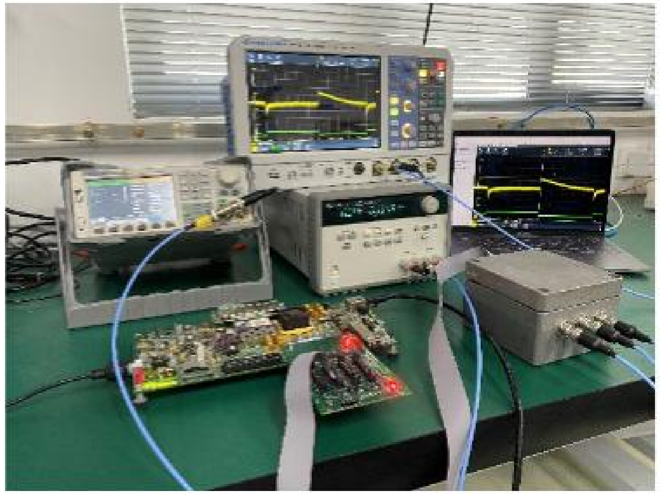
- Successful measurement of alpha particle tracks has been achieved.

Readout ASIC Option II - CSA only

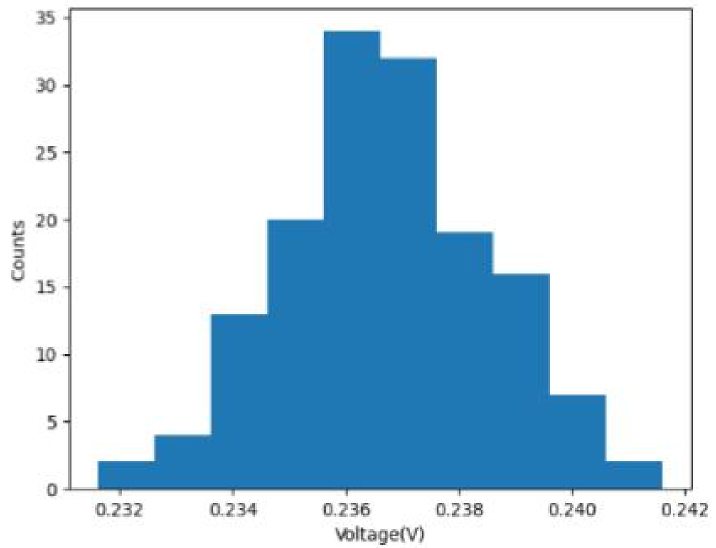






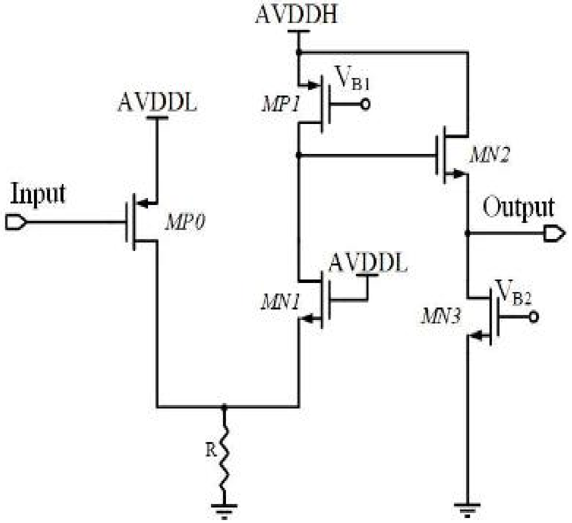


ENC : ~ 97 e^-



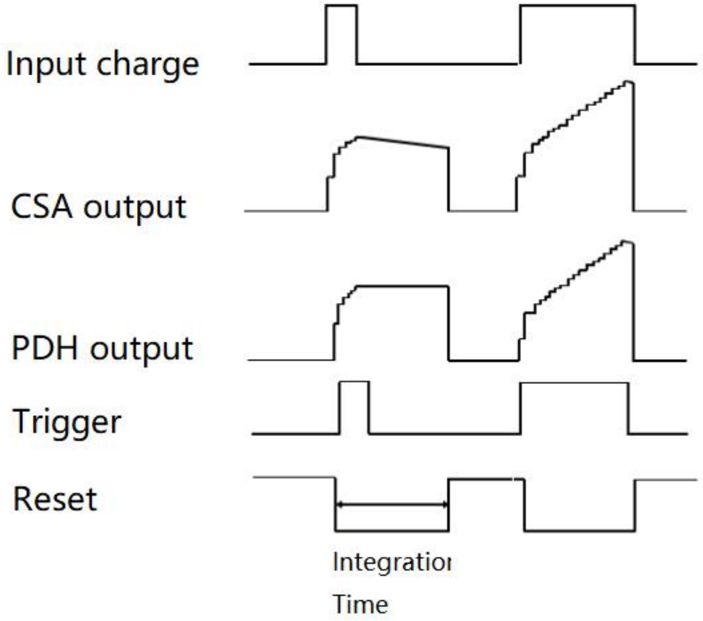
Next Step for the ASIC design

- Reduce Noise of the CSA



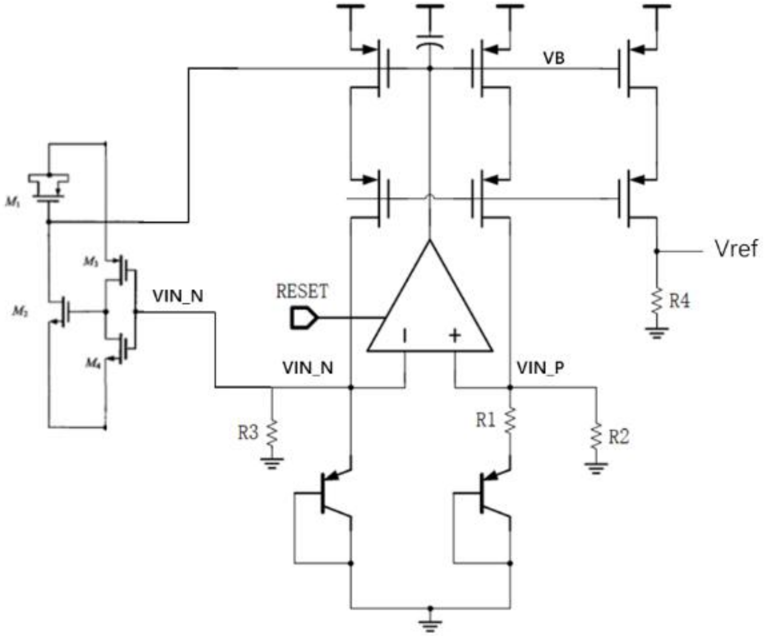
- PMOS input reduce flicker noise.
- Increase the transconductance (gm) of the input transistor.
- Change process
- Modify the reset method to eliminate the noise from feedback resistors.

- Implmentation of Continous Integration

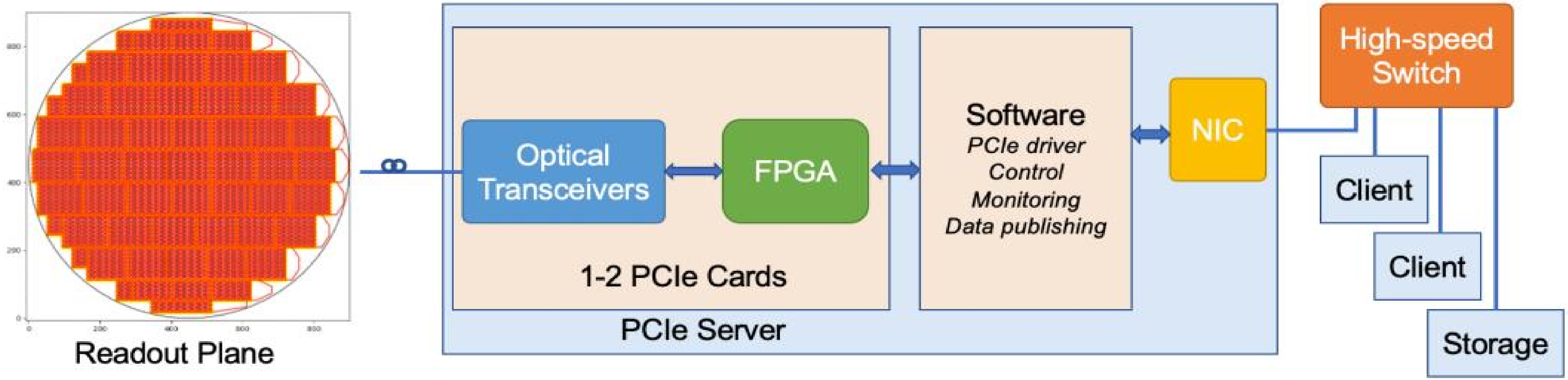


- Baseline Hold Circuit
- PDH based baseline feekback adjustment
- Self-Reset with controllable duration

- Include on-chip DAC



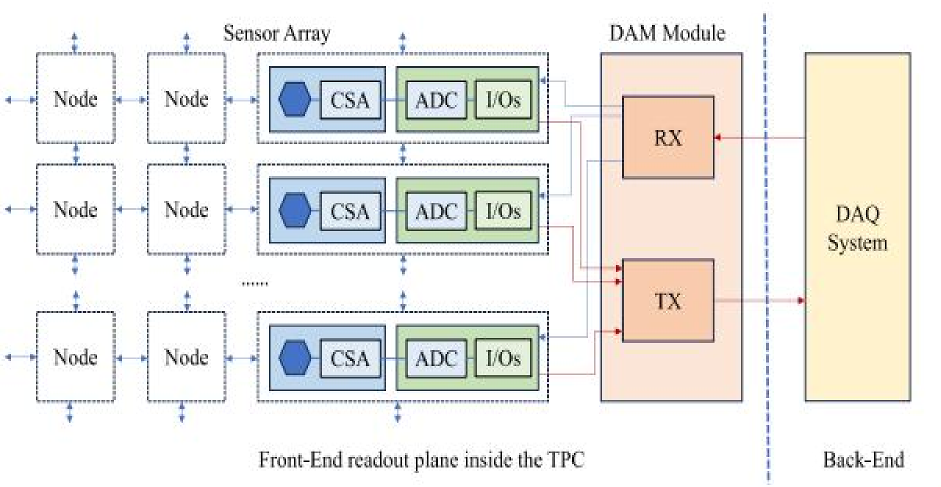
The Readout System

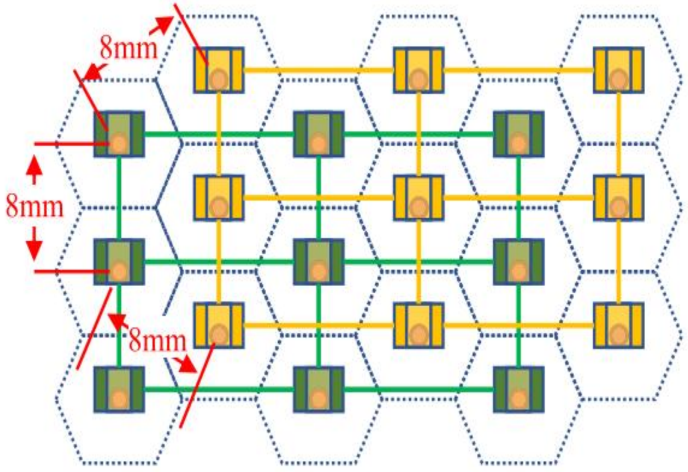


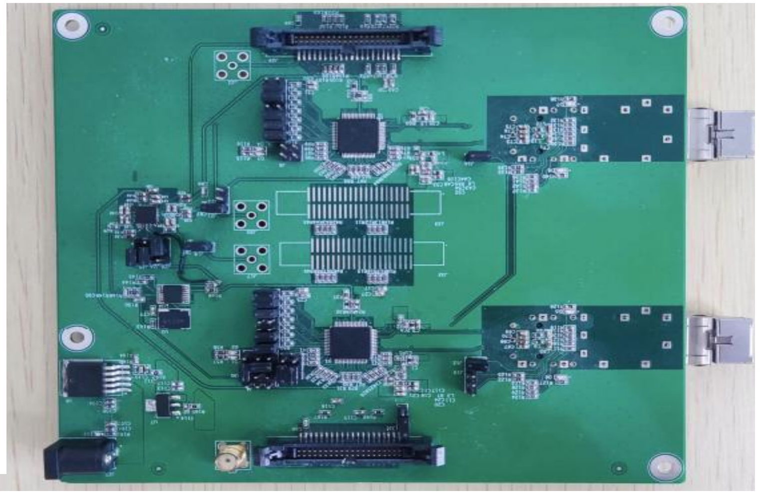
- There are around 15 000 charge sensors on the readout plane whose effective area is about 0.5 m^2
- Each Module contains 256 Sensor
- Flexible Printed Circuit Board (FPCB) for low background noise
- PCIe based data acquastion card

The Readout System

- Data aggregation modules (DAMs) at the edge aggregate slow parallel data links to fas serial data links

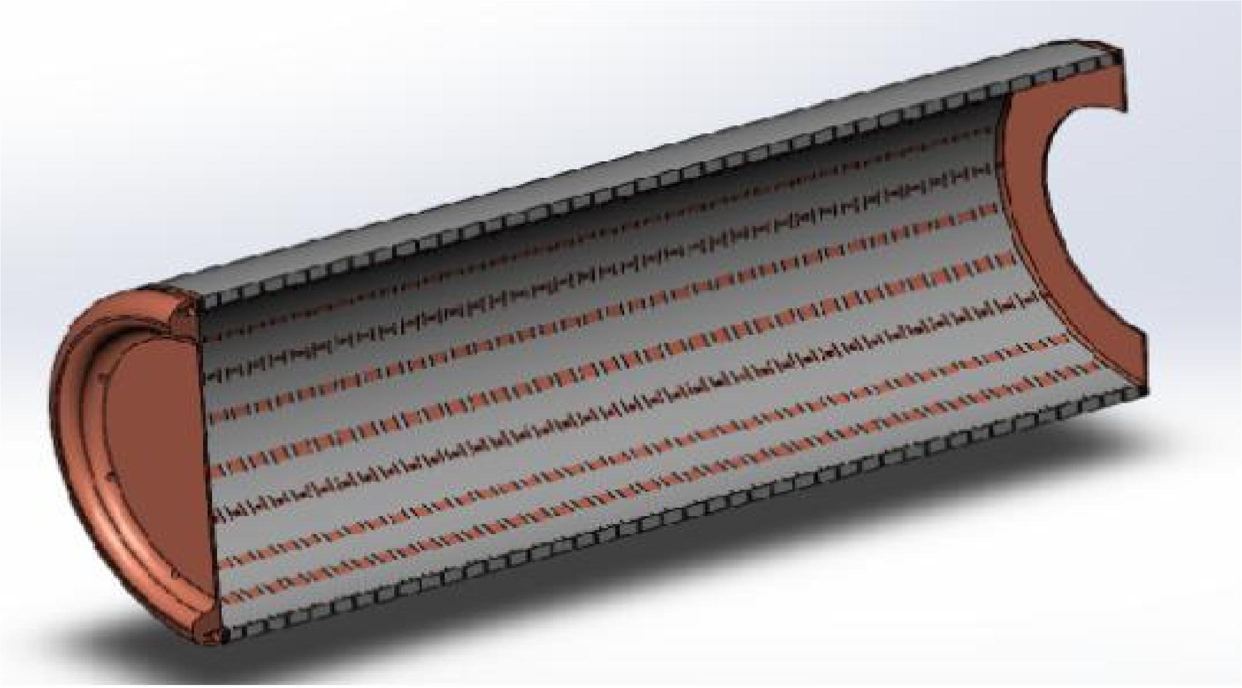


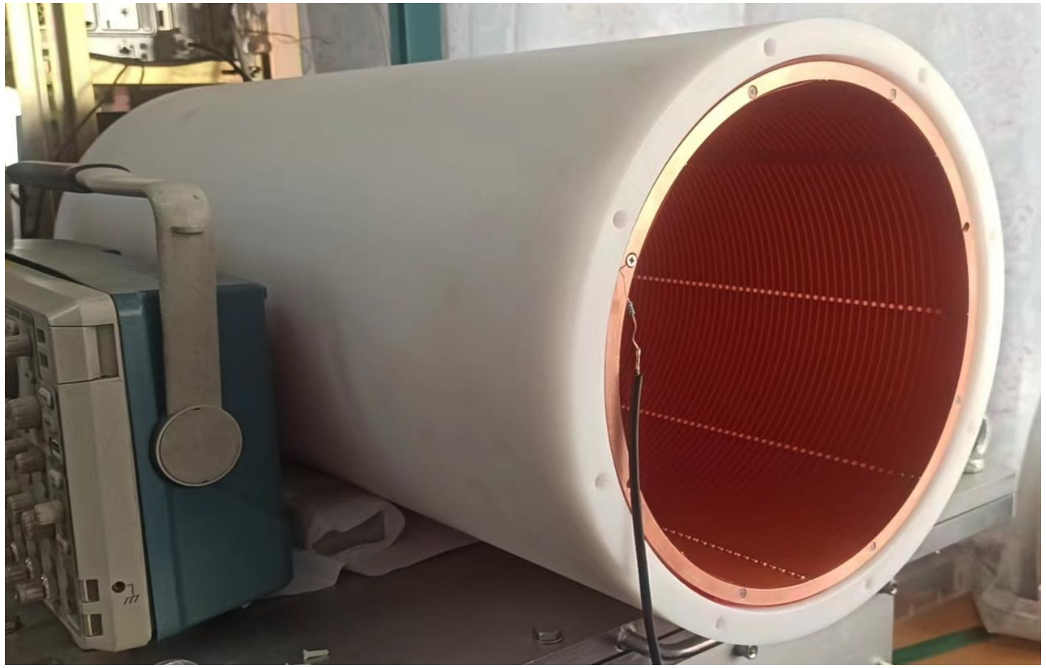




- PCIe backend Card
  - Kintex Ultrascale+ KU15P FPGA with 24 GTY and 32 GTH high-speed transceivers is utilized
  - 24 optical links up to 28Gbps
  - 16-lane PCIe interface Gen3
  - DDR4 slot and two OCuLink connectors

The TPC field Cage





Electrical field ~400V/cm -> Drift velocity of negative ions approximately 20cm/s.

Composed of multiple flexible printed circuit boards (FPCBs)

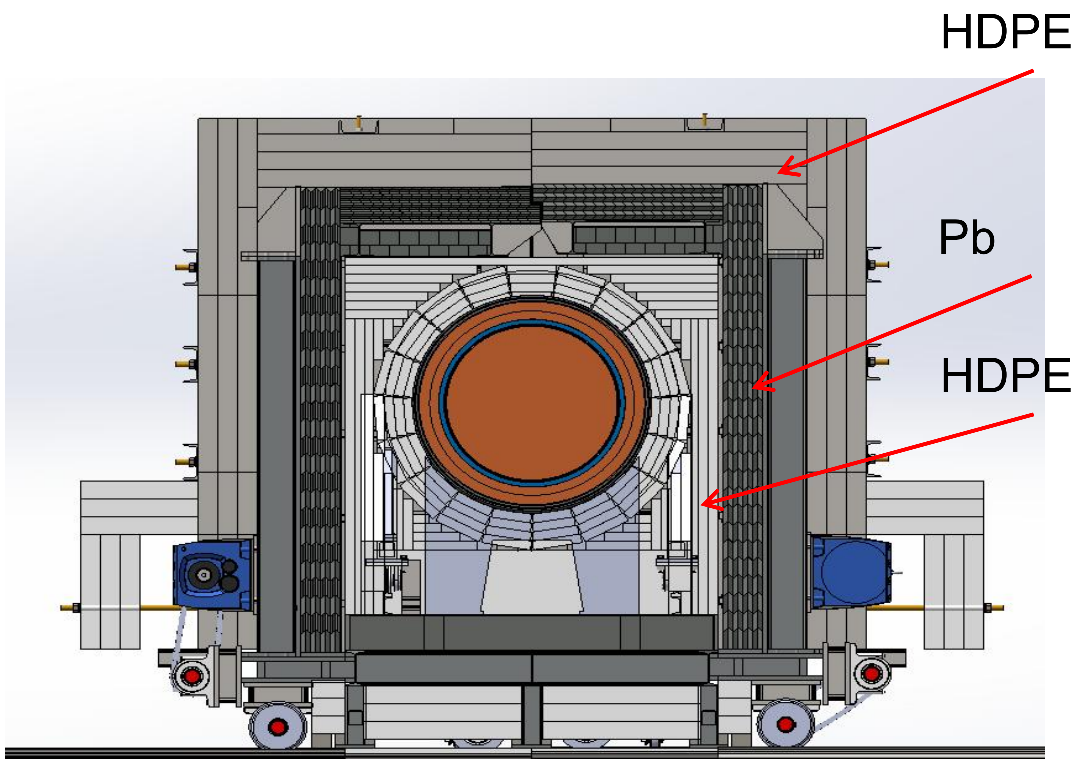
The cathode is made of low-background oxygen-free copper

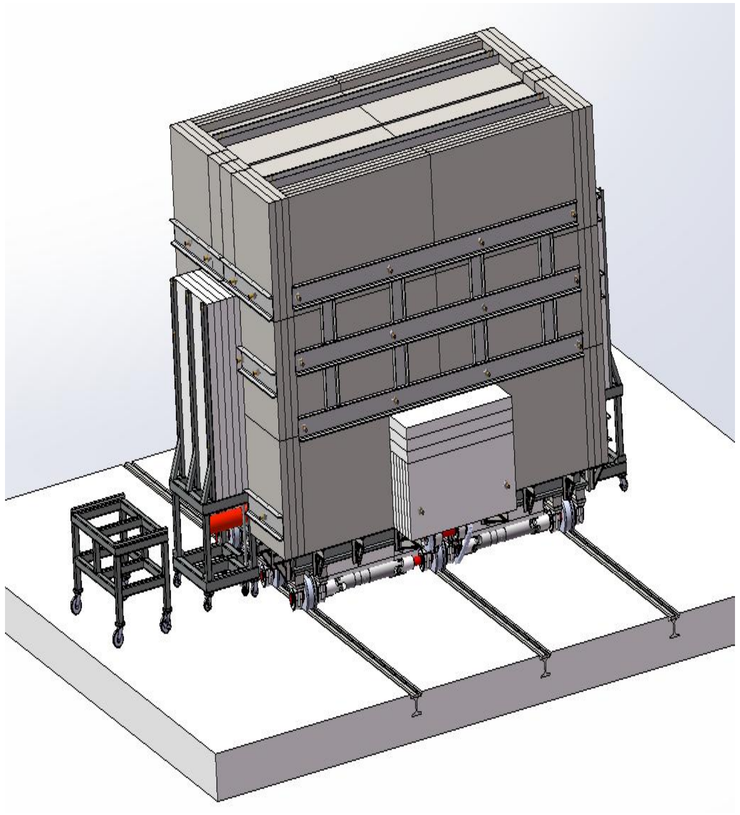
2.5cm thick Polyoxymethylene (POM) insulator

Inner Copper Shielding

- Consists of the barrel and the end
- Low-radiation oxygen-free copper
- 12 cm thick, 9 ton weight

External Shielding



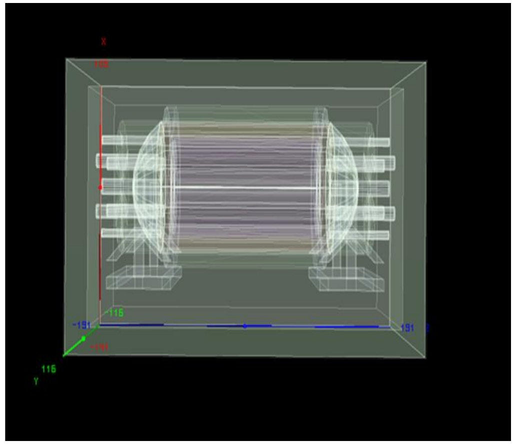


- 20 cm thick of Pb to stop γ
- High density polyethylene (HDPE) to stop neutrons
  - between the Pb layer and pressure chamber
  - 30 cm thick outside Pb layer

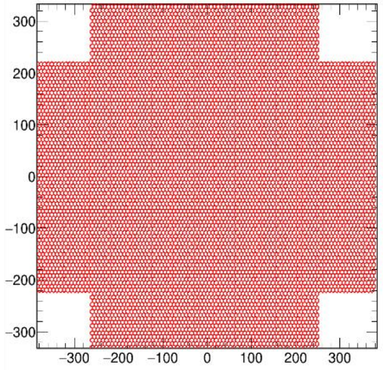
- Mechnical Supporting
  - ➢ The central part is fixed
  - ➢ The left and right parts can be open and moved.

Simulation Software

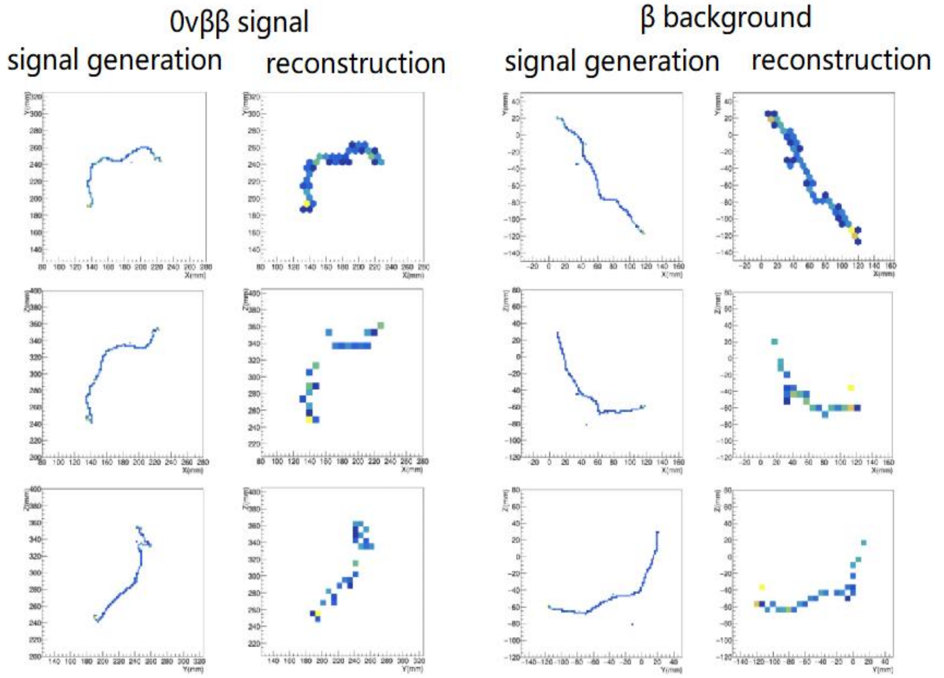
- The software is capable of simulating beta decay signals, various backgrounds, and reconstructing the spatial distribution of energy loss, total energy, and other information for each event



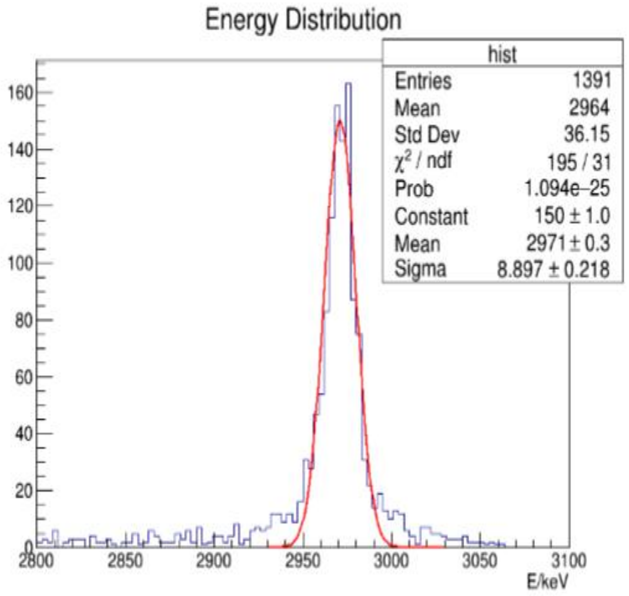
- ☐ The overall architecture of the detection system



- ☐ The readout plane

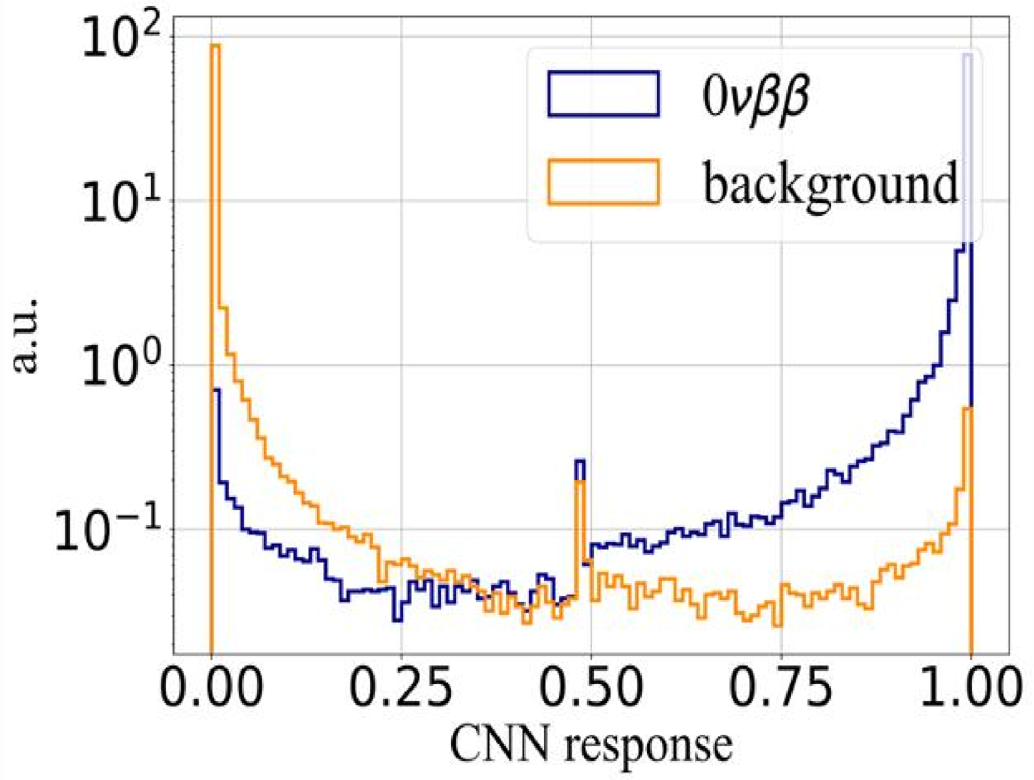


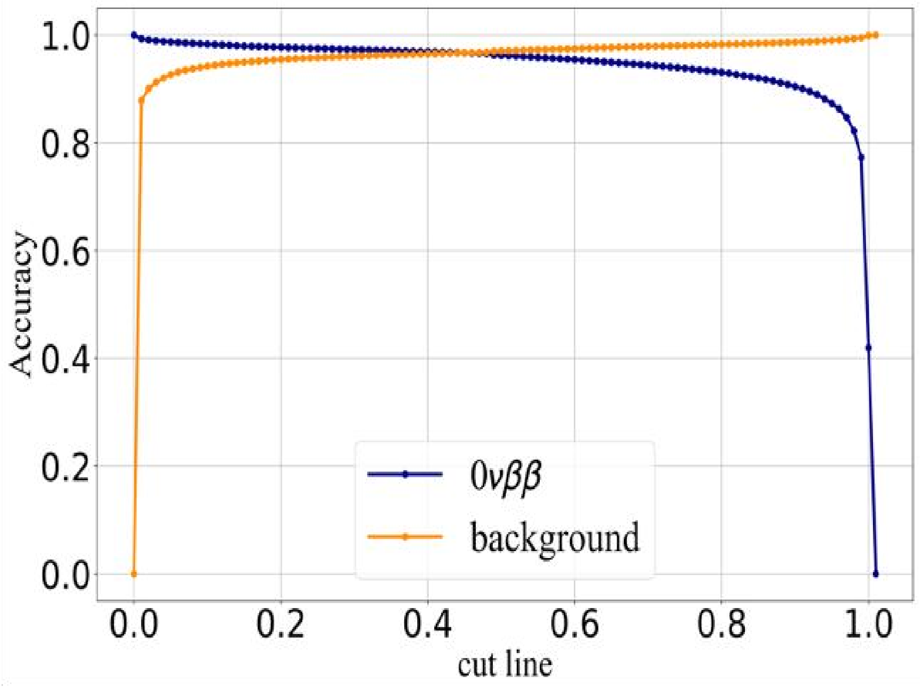
- ☐ The energy deposition location distribution of 0νββ signal events and β background events, as well as the reconstructed charge position distribution



- ☐ **0.7% Energy resolution can be expected**

Background suppression with CNN



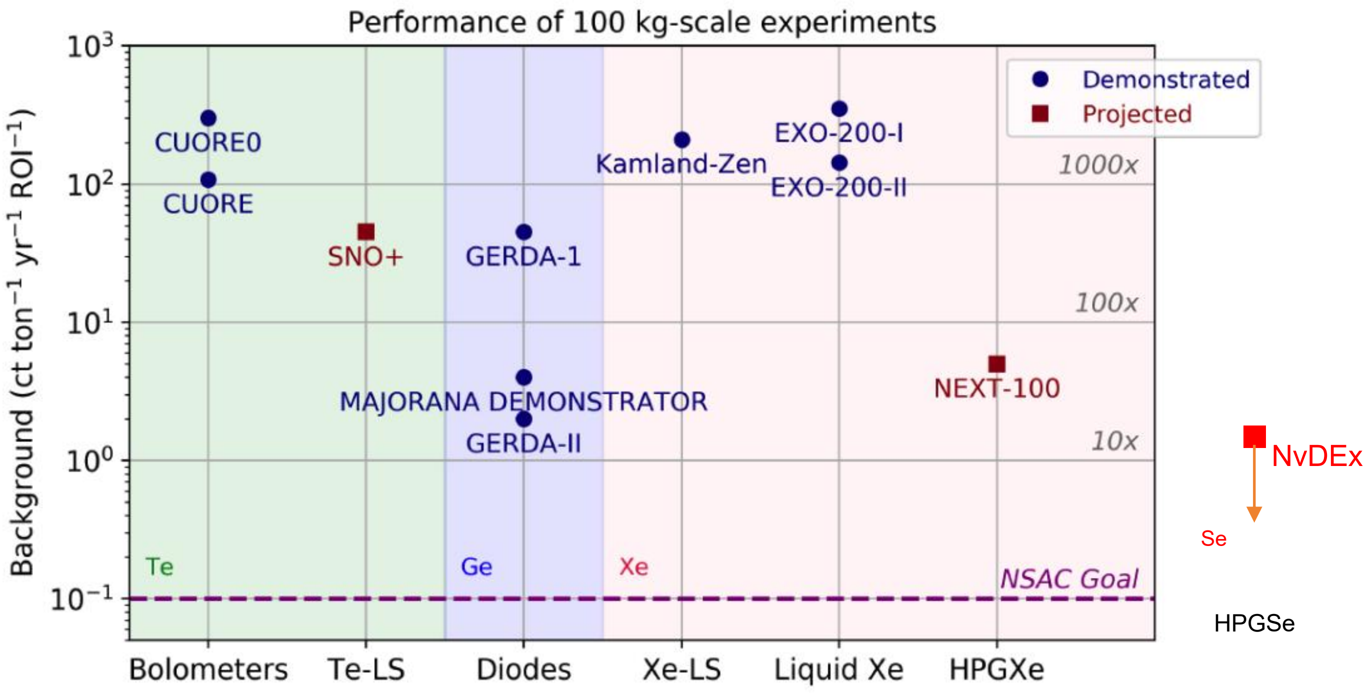


Convolutional Neural Network (CNN) is employed for signal-background discrimination

- Utilizing the distinct geometric characteristics of signals and background events,
- The CNN response value distribution for $0\nu\beta\beta$ signals and β background events shows a significant difference.
- It is possible to reject 98.6% of background events (CL > 90%)

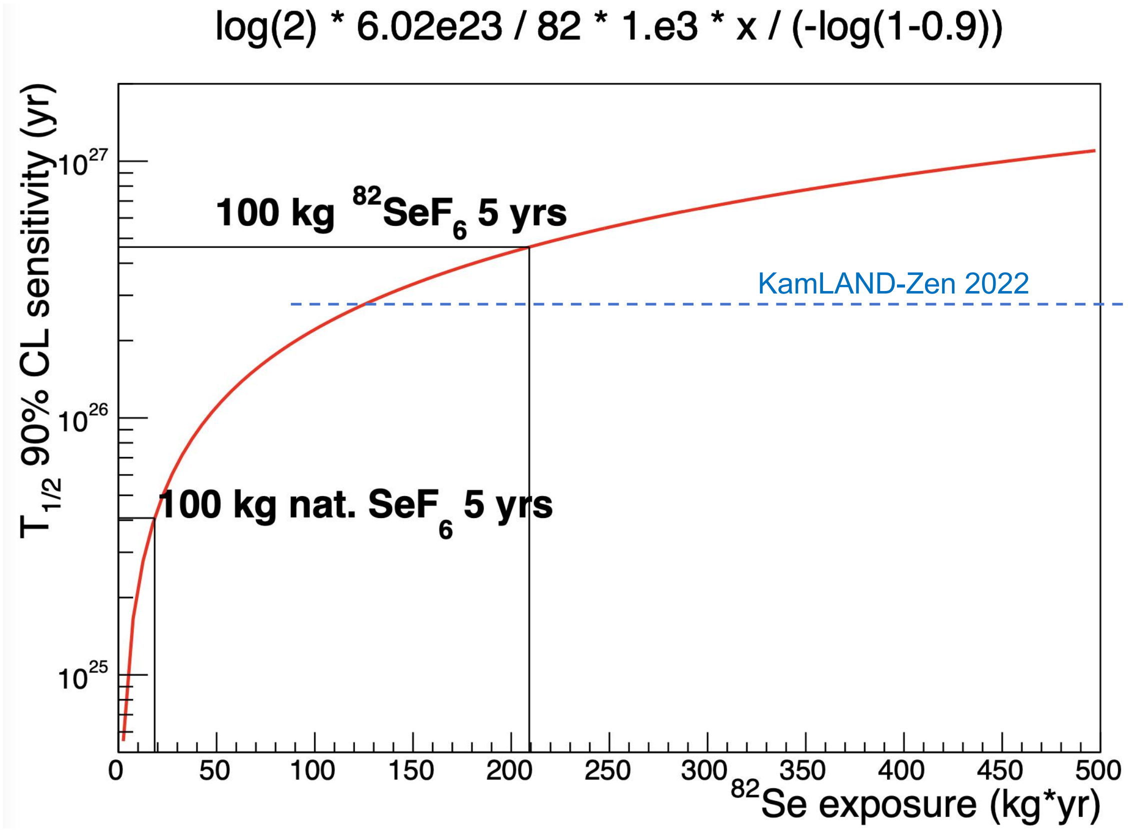
Background Estimations

"100kg-class" experiments:



- Natural radiation γ is the dominant background source for NνDEx
- In total, ~<0.05 counts / year in ROI ⇒ ~<1 cts / (ton yr ROI)
- Very good potential for a future multi-ton scale experiment reaching for normal hierarchy $m_{\beta\beta}$ region

Sensitivity Estimation



- Within 5 years the background in ROI ~< 0.25 counts, basically 0 background
- $T_{1/2} > 4 \times 10^{25}$ yr at 90% CL, with 100 kg natural SeF_6 (only 3.7kg ^{82}Se) 5 yrs
- $T_{1/2} > 4 \times 10^{26}$ yr at 90% CL, with 100 kg $^{82}SeF_6$ 5 yrs

NνDEx Collaboration

- 1st NνDEx workshop in 2019
- >30 collaborators from 9 institutes now