2024 Joint Workshop of FKPPN and TYL/FJPPN
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French-Korean Collaboration in FAZIA

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and
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for

FKPPN-FAZIA-FKC

Brief history of French-Korean Collaboration

Before 2019:

- The Korean group (part of LAMPS Collaboration) was designing the Si-CsI telescope for the low-energy (a few tens MeV per nucleon) nuclear collision experiments at RAON, which is the new radioactive-ion beam facility being built in Korea.
- The International Advisory Committee of RAON reviewed the status of the detector development and suggested to collaborate with FAZIA in Europe, because FAZIA had been operating the most advanced Si-CsI detector system for nuclear physics.
- We started the discussion with some FAZIA members to join the Collaboration in various Conferences and meetings.

In 2019

- A group of Korean researchers visited GANIL in May and participated in the E789 experiment.
- Three professors (B. Hong @ Korea Univ., M. Kweon @ Inha Univ., I. Hahn @ Ewha Womans Univ.) attended the FAZIA Workshop at GANIL in September 2019 and presented the application to officially join the Collaboration.

MoU

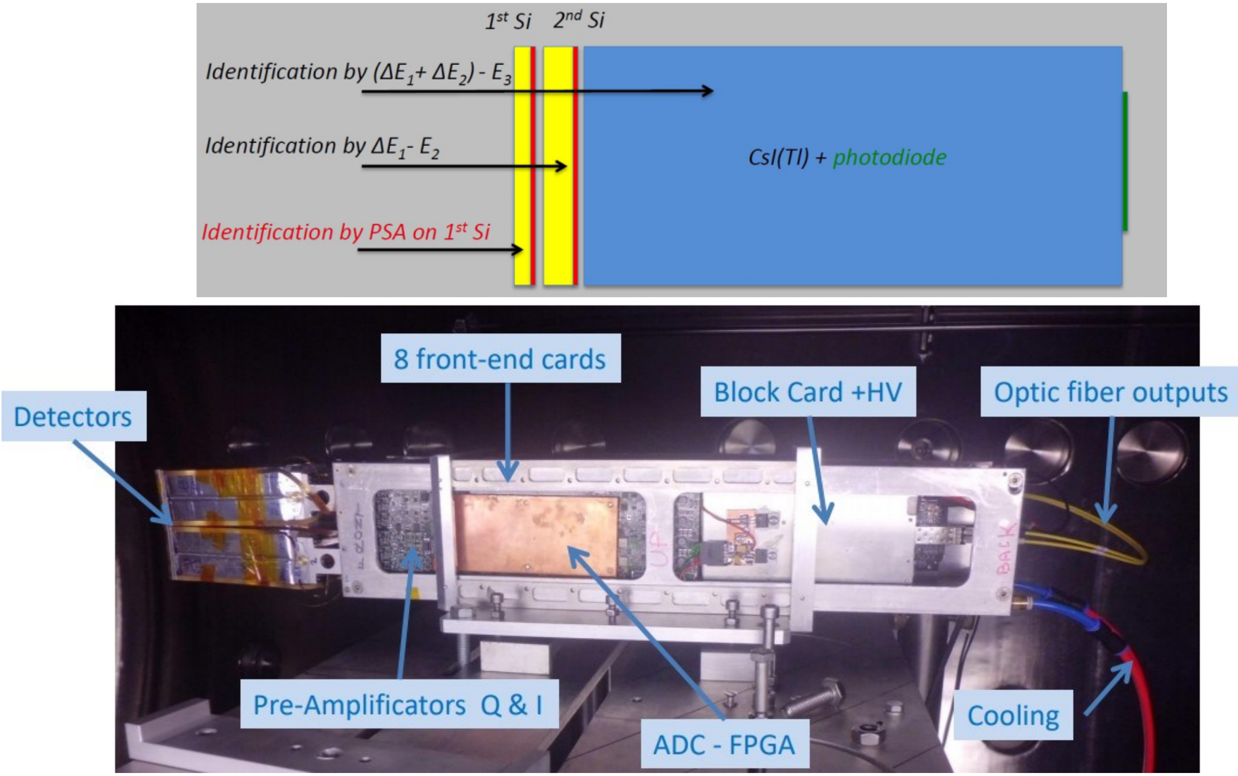
- The Center for Extreme Nuclear Matters (CENuM), representing the whole Korean group, signed on the MoU in 2020.
- Signed the new MoU for 2023-2027

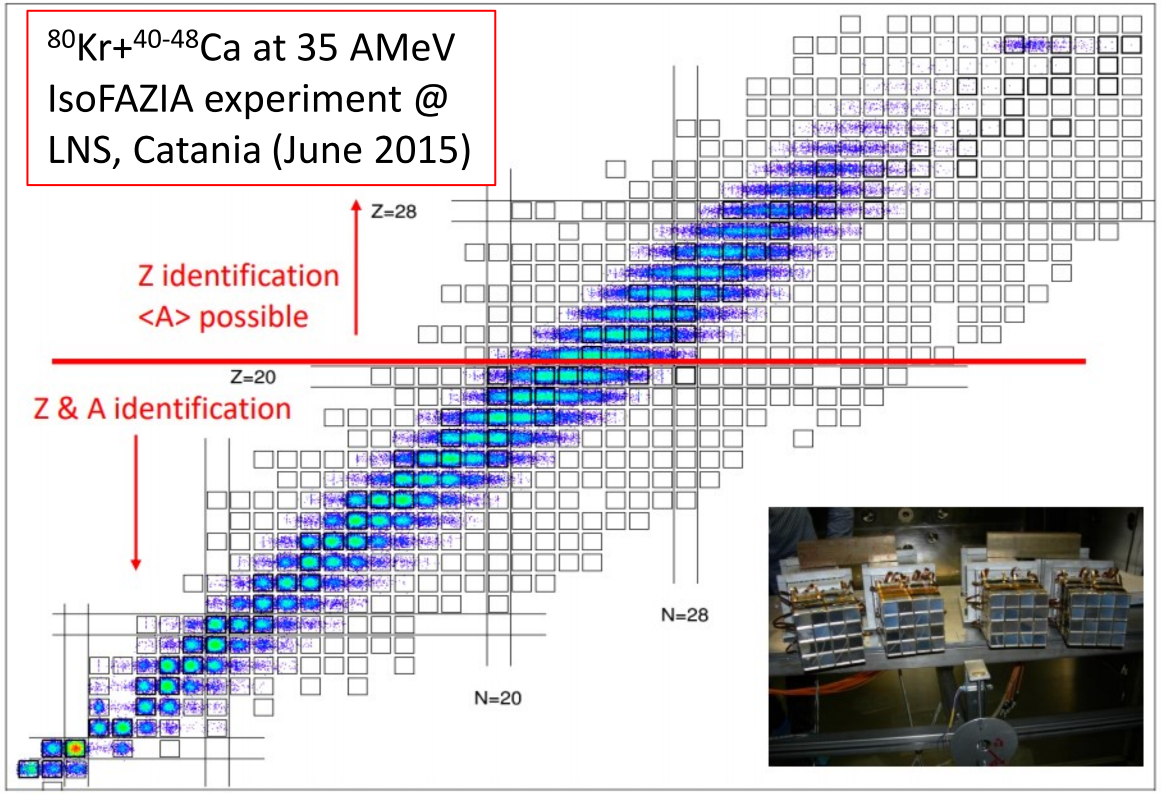
FAZIA 101

- FAZIA: Charged-particle detector system for heavy-ion collision studies in intermediate beam energies (presently located at GANIL)
- Collaboration status
  - 5 countries (France, Italy, Korea, Poland, Spain)
  - ~30 physicists & ~10 students

FAZIA 101

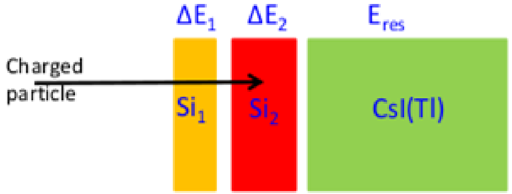
- One FAZIA block consists of 16 Si_1+Si_2+CsI telescopes (Cross-section of each: 2X2 cm^2)
  - Si_1(nTD): 300 μm thick, Si_2(nTD): 500 μm thick, CsI: 10 cm thick (photodiode readout)
  - Refining Pulse-Shape Analysis (PSA) techniques for identification in a single detector
  - Excellent isotopic resolution for charged particles in heavy-ion collisions at the beam-energy range from 15 to 100 AMeV, which is mandatory for the radioactive ion beam experiments.

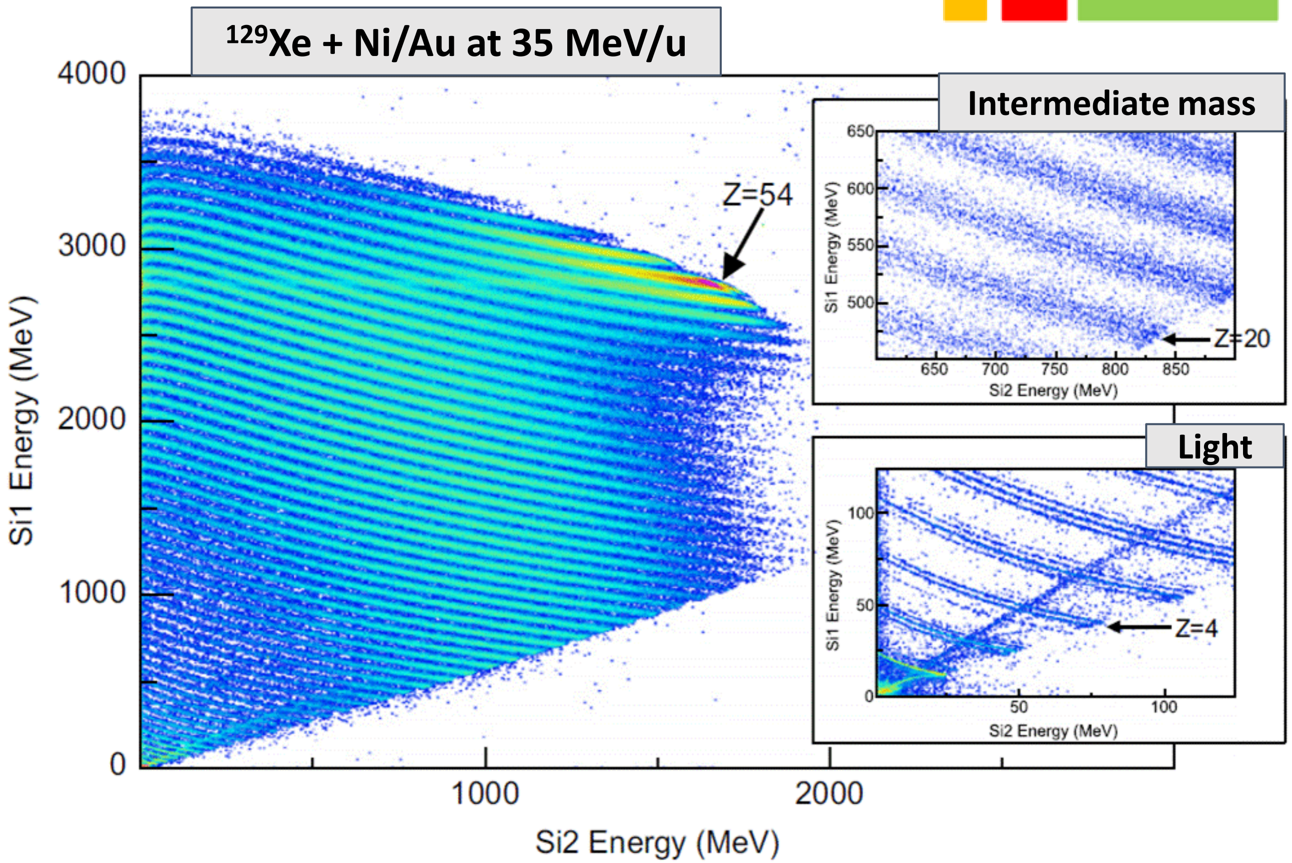


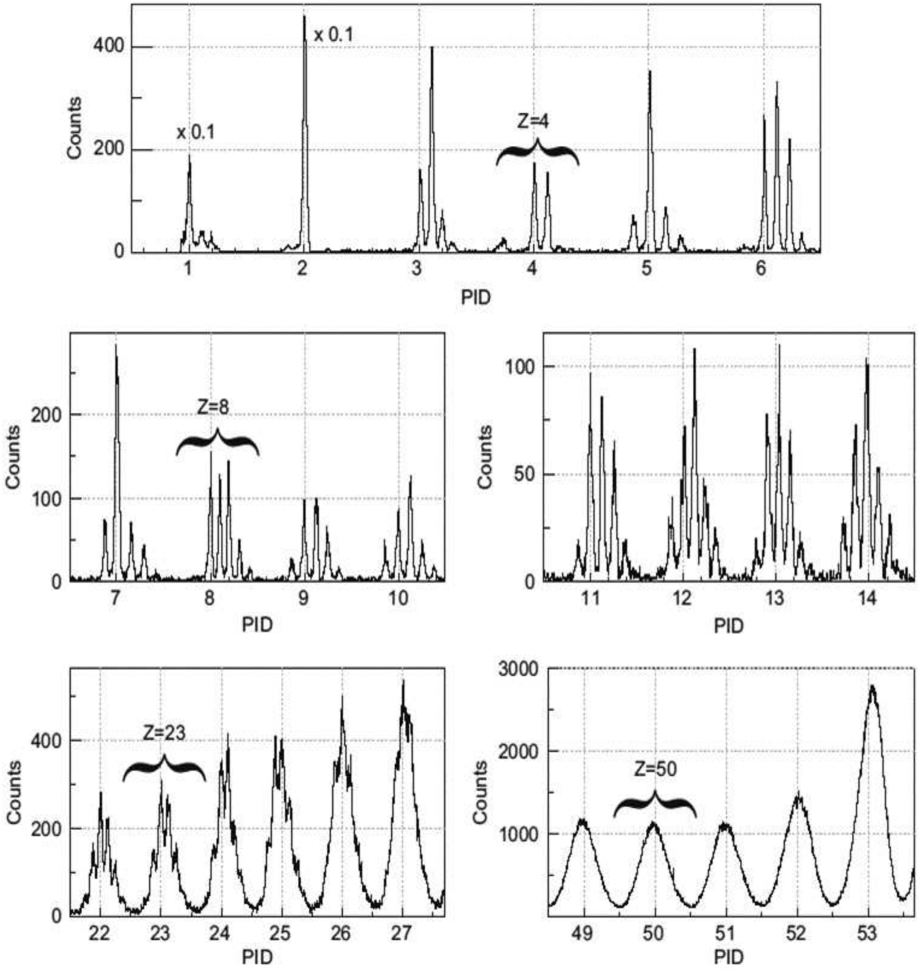


FAZIA 101

- PID: EPJA 50, 47 (2014)







- Mass discrimination up to $Z\sim26$ and charge identification up to $Z\sim54$

FAZIA 101

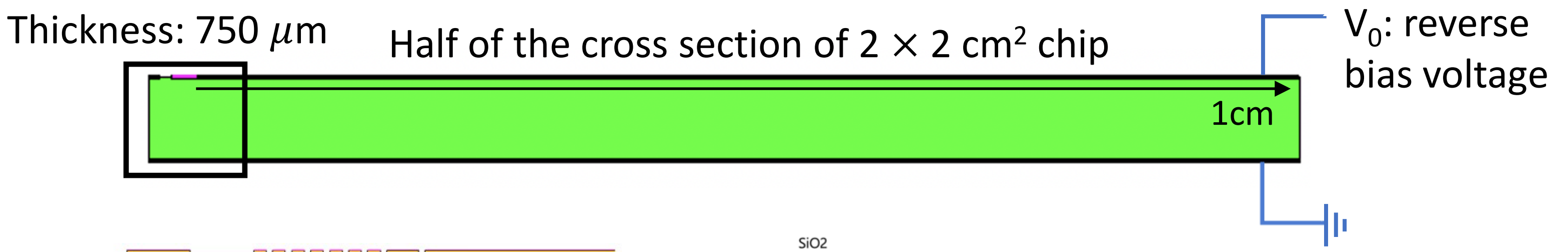
- Scientific goal
  - Detailed understanding of the nuclear Equation of State (EOS) and symmetry energy for both microscopic (nuclei) and macroscopic (neutron stars) objects
- Physics experiments with Korean participation so far
  - E789 (2019): Isospin transportation and the density dependence of the symmetry energy
  - E818 (2022): Characteristics of the warm dense nuclear matter in low-density region
- Long-term plan
  - Extension of the applicable beam energy range using thinner and thicker Si sensors
  - Application of the modern technology to the next generation detectors and FEE cards
  - Manufacturing more FAZIA blocks in Korea, especially, for the experiments at RAON
  - Exploration of the flexible installation scheme in the limited space of vacuum chamber
- Goal of FAZIA-FKC for the next 2-3 years
  - Production of four new FAZIA blocks in Korea
  - Analysis and publication of the directed and elliptic flow using the INDRA+FAZIA data set

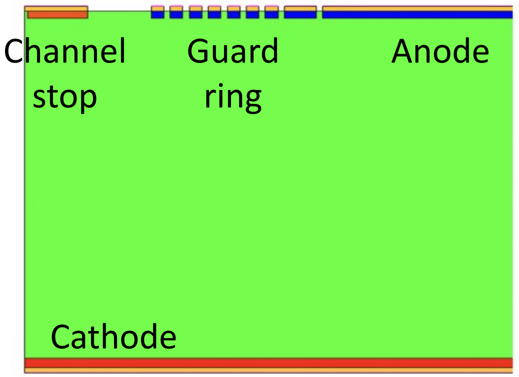
Participants

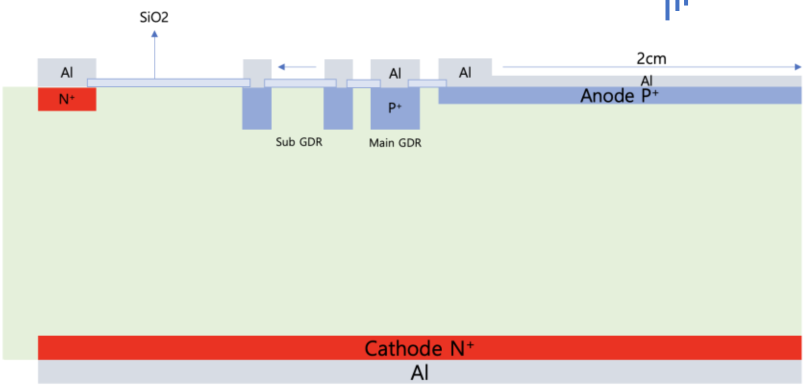
French side			Korean side		
Name	**Position**	**Affiliation**	**Name**	**Position**	**Affiliation**
Leader: **Le Neindre, Nicolas**	CR	LPC Caen CNRS IN2P3 & University	**Leader:** **Hong, Byungsik**	Professor	Korea University (CENuM)
Bonnet, Eric	CR	Subatech Nantes CNRS IN2P3	**Kweon, Minjung**	Professor	Inha University (CENuM)
Borderie, Bernard	Emeritus	IPNO Orsay CNRS IN2P3 & University	**Kim, Jiyoung**	Postdoc	Korea Univ. (CENuM) & Inha Univ.
Bougault, Rémi	DR	LPC Caen CNRS IN2P3 & University	**Lee, Jong-Won**	Postdoc	Korea University (CENuM)
Chbihi, Abdou	DR	GANIL	**Nam, Seon Ho**	Student	Korea University (CENuM)
Ciampi, Caterina	Postdoc	GANIL	**Park, Jeonghyeok**	Student	Korea University (CENuM)
Durand, Dominique	DR	LPC Caen CNRS IN2P3 & University	**Kim, Giyoung**	Student	Inha University (CENuM)
Fable, Quentin	Postdoc	L2IT Toulouse CNRS IN2P3	**Hahn, Kevin Insik**	Professor	CENS, IBS
Frankland, John	CR	GANIL	**Kim, Sunji**	Postdoc	CENS, IBS
Gruyer, Diego	CR	LPC Caen CNRS IN2P3 & University			
Lopez, Olivier	DR	LPC Caen CNRS IN2P3 & University			
Rebillard, Alex	Student	LPC Caen CNRS IN2P3 & University			
Valente, Antonin	Student	LPC Caen CNRS IN2P3 & University			
Vient, Emmanuel	EC	LPC Caen CNRS IN2P3 & University			

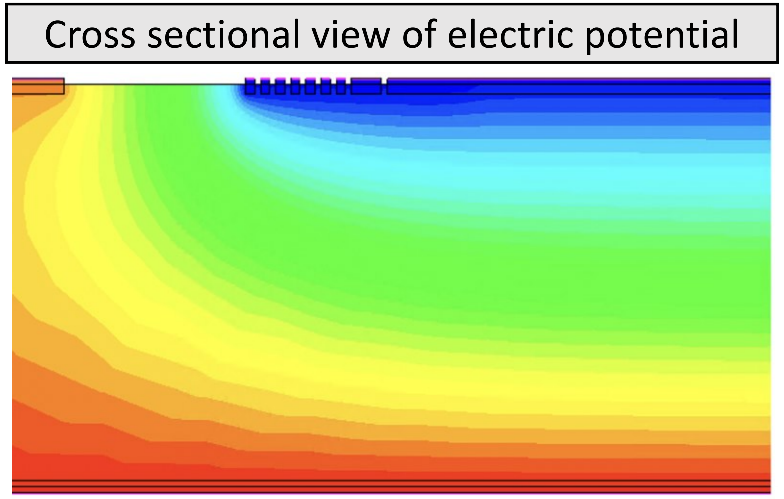
Design of PiN sensor using Synopsys TCAD*

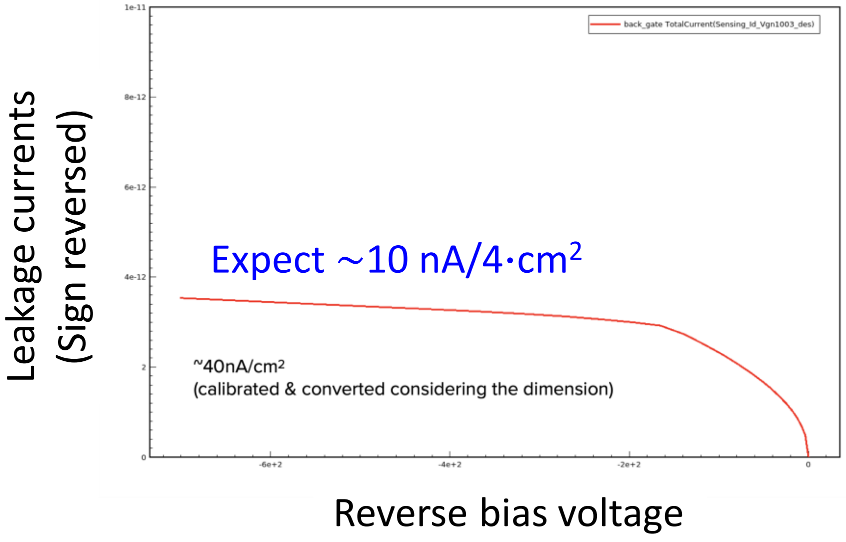
* TCAD: Technology Computer Aided Design







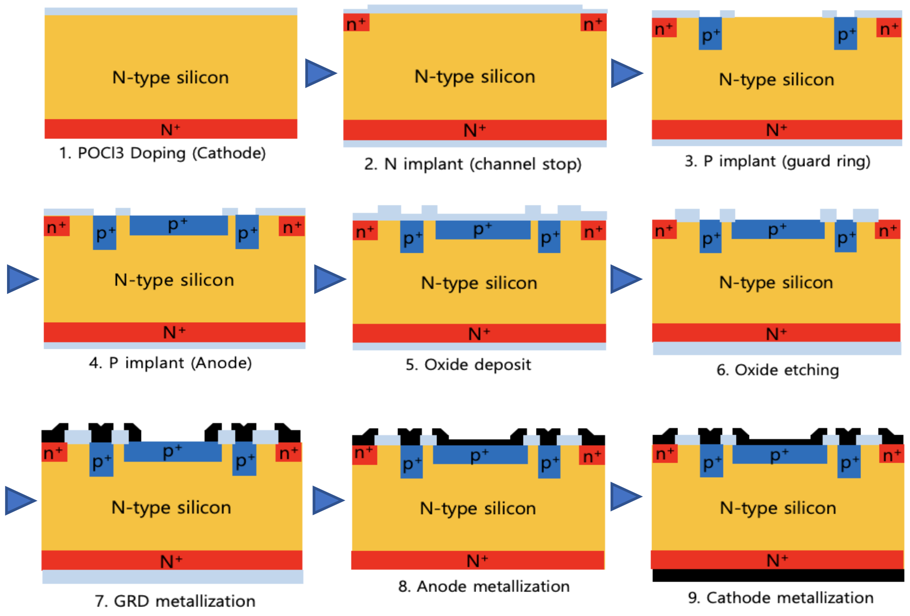




Input parameter				
Temp.	300 K		Doping density	
V_0	0 ~ -700 V		(blue)	P^+ Boron 1×10^{19} cm^{-3}
Carrier lifetime	e^-	1×10^{-4} s^{-1}	(green)	N^- Phosphorus
	hole	3×10^{-4} s^{-1}	(red)	N^+ Phosphorus

Development of Si sensors

Part of the Si sensor process flow



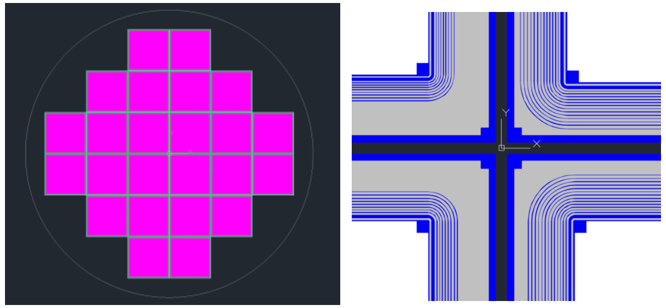
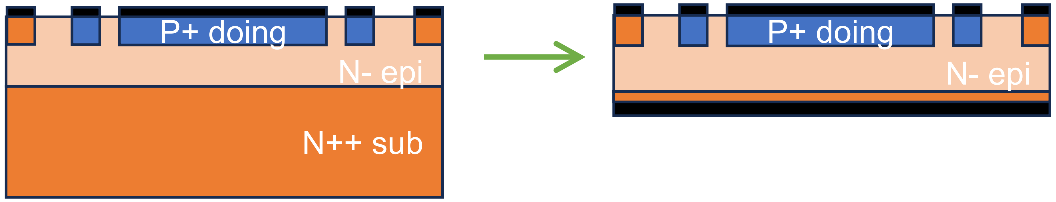
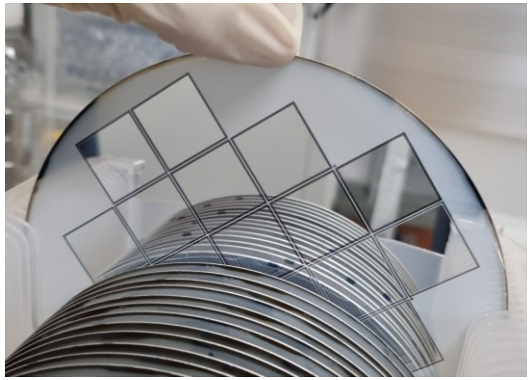


Photo mask (by MicroImage): Tested various guard ring patterns & different sensor designs

Barrier metal effect for thick (750 µm) sensors

Thinning of epitaxial wafer for thin (115 µm) sensors



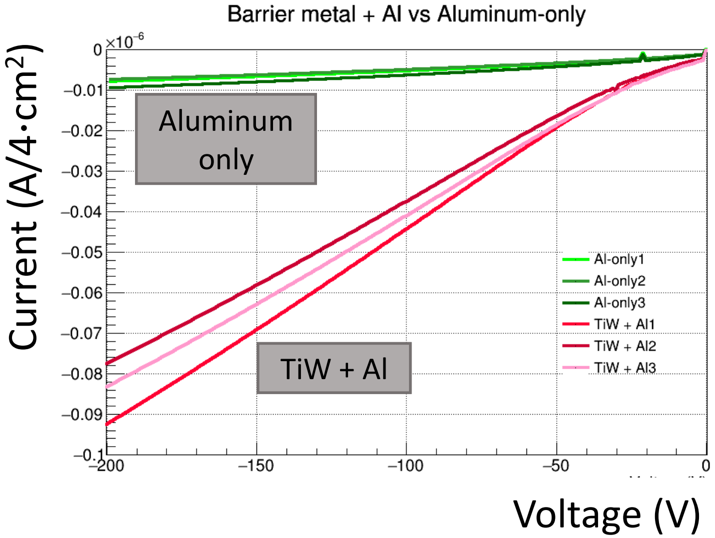


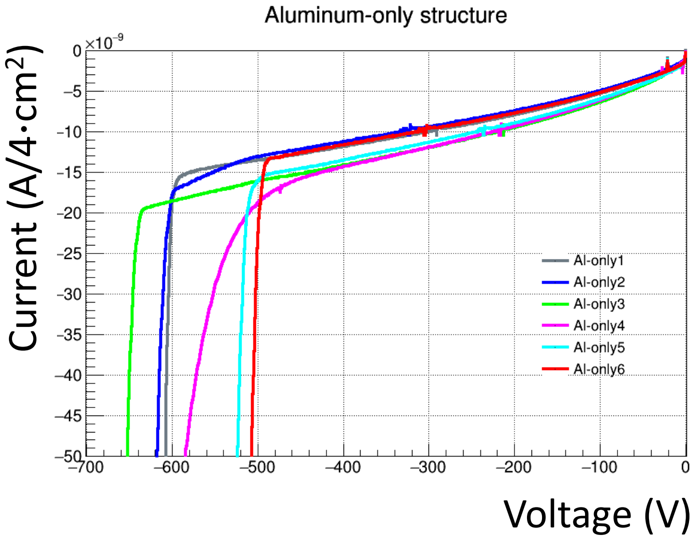
Wafer processing (by ETRI)

Thinning (by TRinno Tech) & dicing (by MEMSPACK)

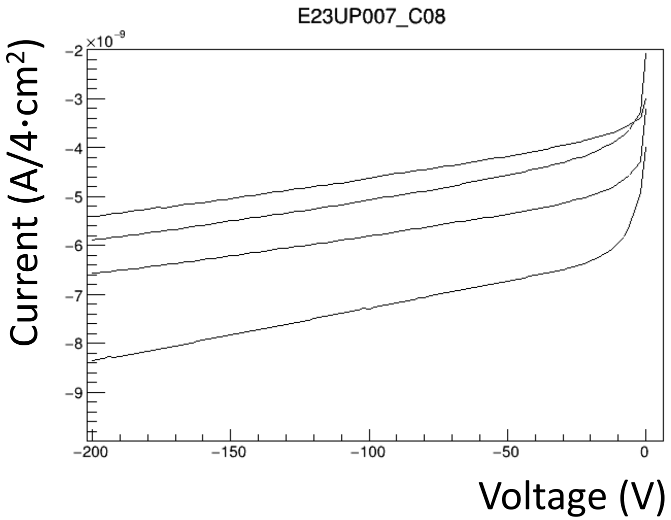
Test results

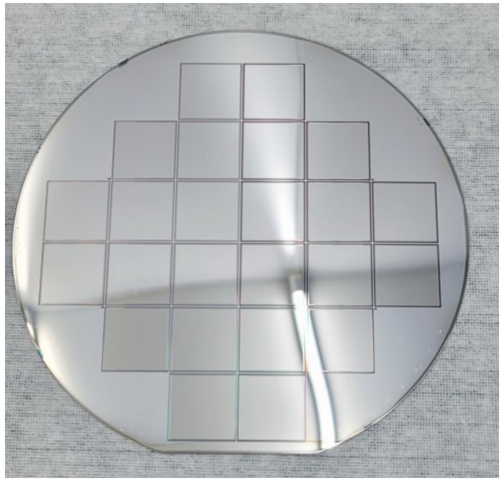
- Effect of barrier metal on anode
  - Tested with 750 µm thick sensors
  - Observed a large effect of barrier metal on the leakage currents
  - *Sensors with Al only show much better performance* than the one with barrier metal
  - Breakdown voltage w/o barrier metal ~600 V (cf. $V_{depletion}$ = 400 V)





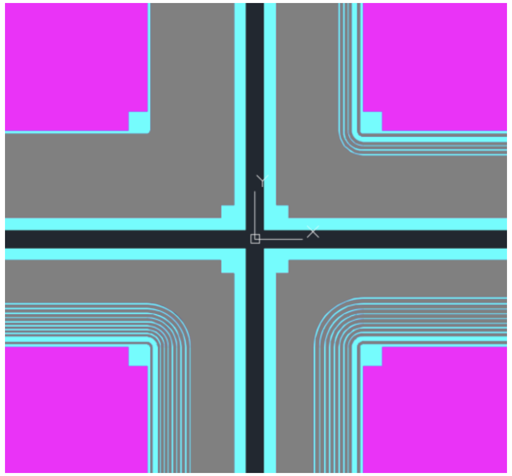
- Performance of thin sensors
  - *Wafer-level evaluation* with 115 µm thick sensors
  - Obtained satisfactory leakage currents (≤ 10 nA/4·cm²)
  - Chip-by-chip leakage current measurement is being performed after some post processes (BG & BM).

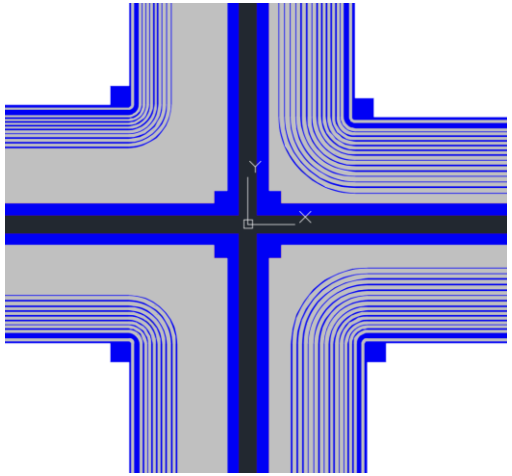


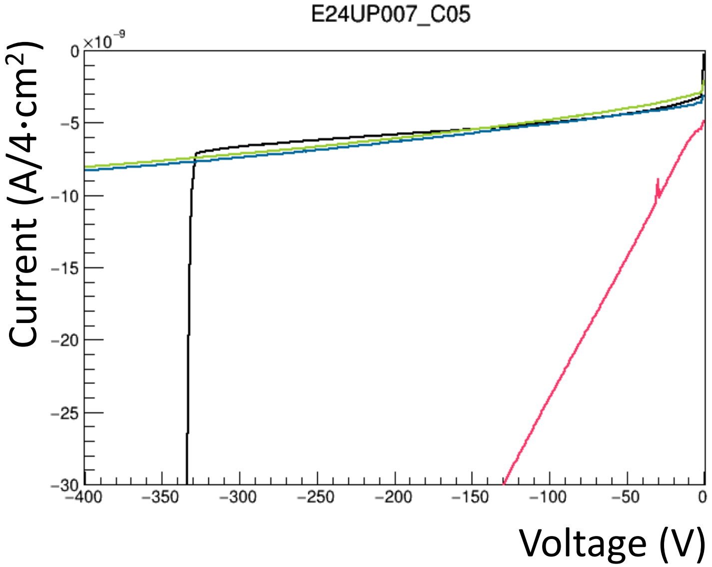


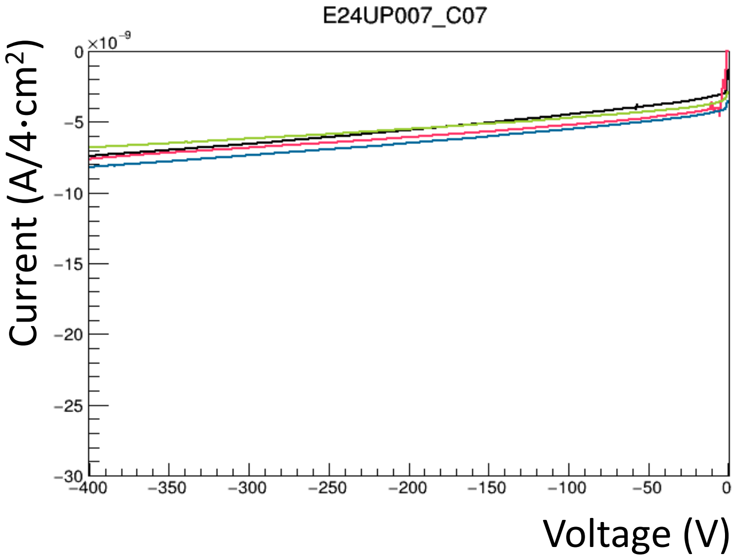
Test results

- Optimization of the chip design
  - *Investigation of the impact of the various guard ring patterns* (# of guard rings & pitches)
  - Photo masks for 115 μm thick sensors are divided into 2X2 matrices for eight different configurations.
  - Plan to select the design for the leakage current to be less than 10 nA/4·cm^2
  - Measurement will be extended to higher voltages to figure out the breakdown voltage.



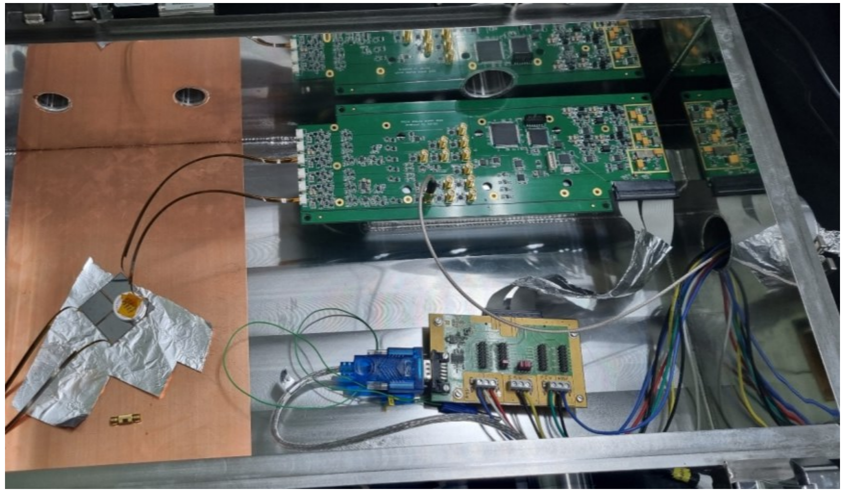


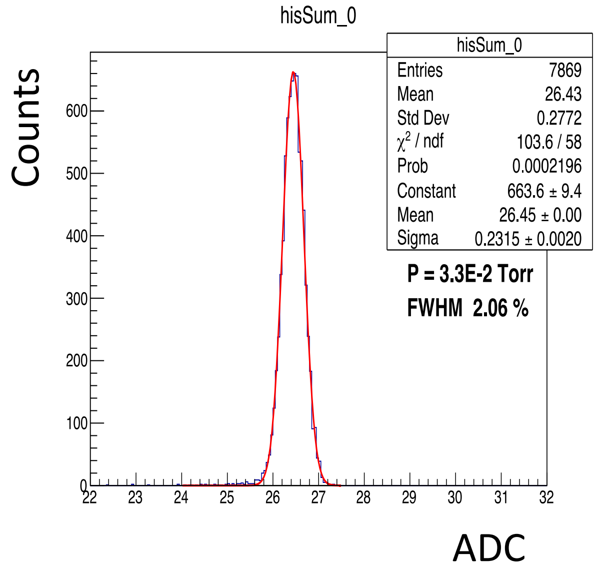




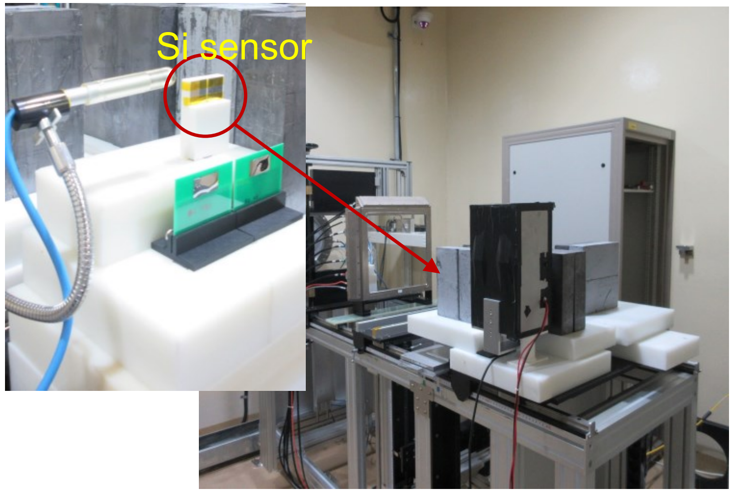
Test results

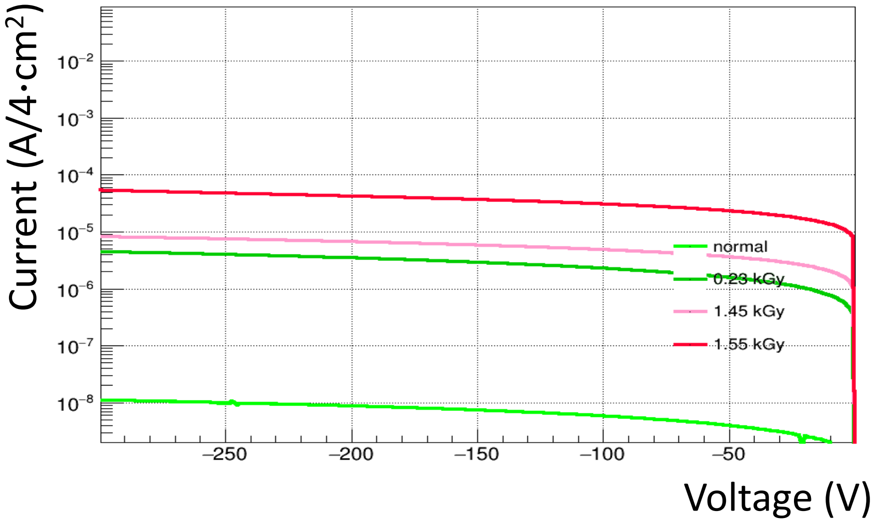
- Energy resolution
  - Measurements were carried out using ^{241}Am α source in the vacuum chamber.
  - Signals were taken by FADC.
  - Energy resolution was estimated to be *~2% (FWHM)* for 750 μm thick sensors.





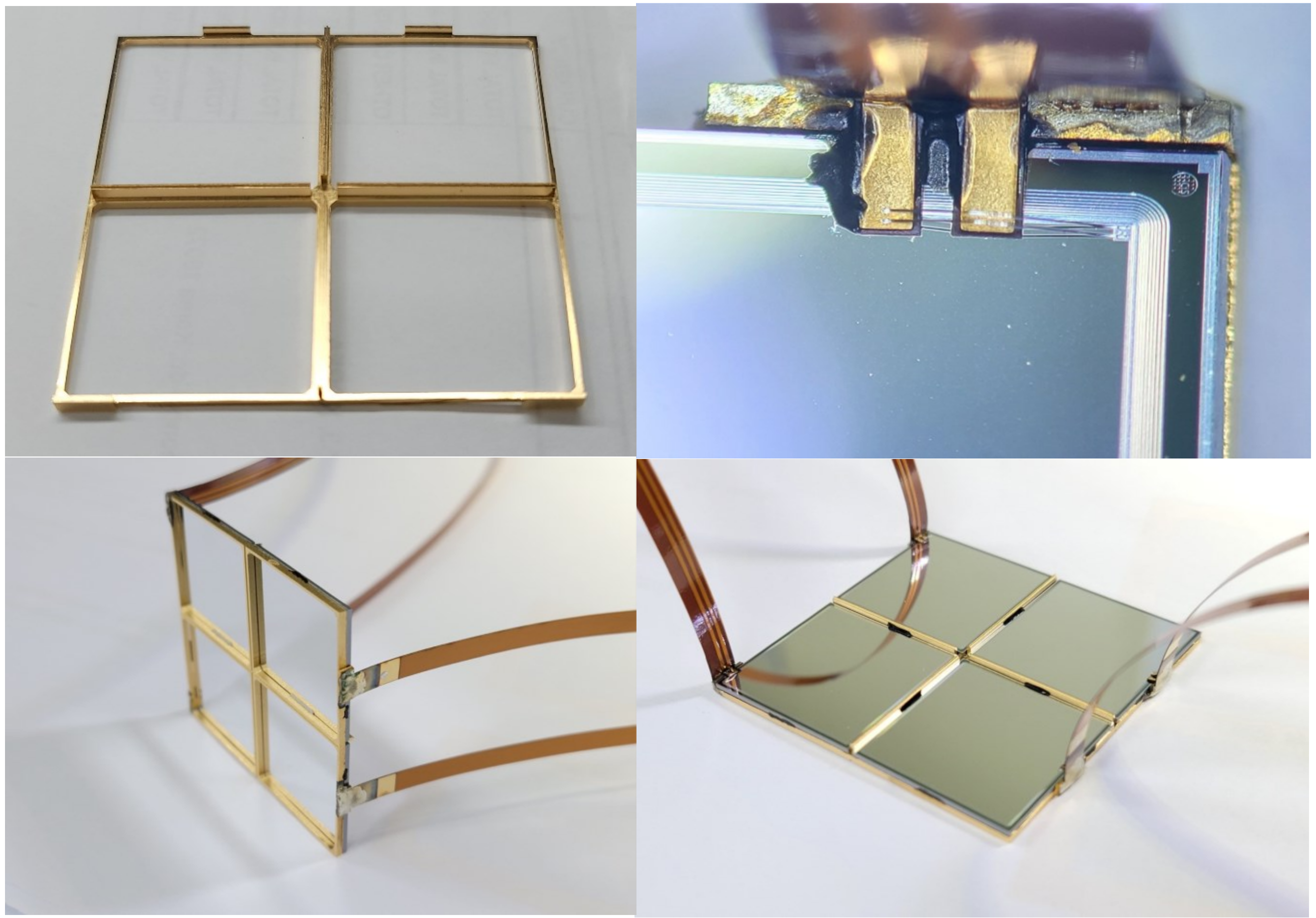
- Radiation hardness
  - Protons beams with energy up to 100 MeV provided by KOMAC (Korea Multi-purpose Accelerator Complex)
  - Radiation exposure level reached up to 1.55 kGy
  - *Larger leakage current due to radiation damage* was observed for higher radiation exposure.

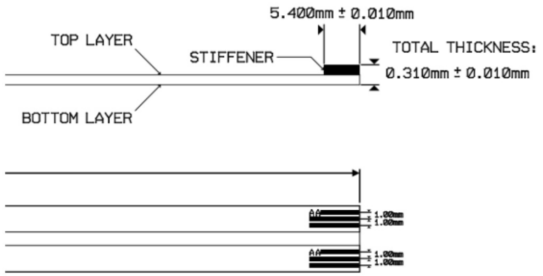




Chip assembly

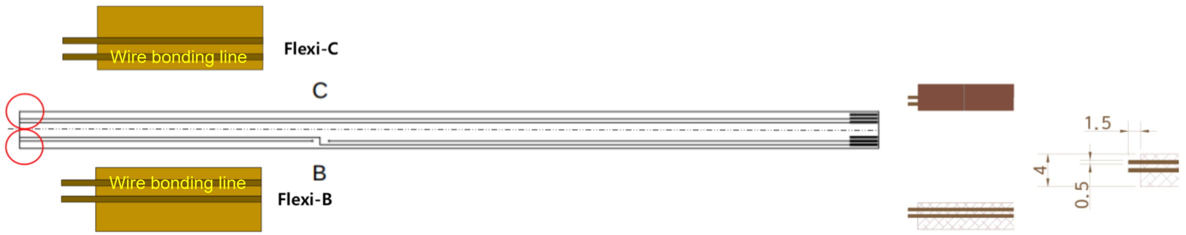
- Detector assembly in quartetto chip frame
  - Four chips are mounted in one quartetto frame.
  - Backside of the sensor is connected to ground.
  - Wire-bonding connection to apply the reverse-bias voltage to the sensors
  - Assembly was carried out in collaboration with MEMSPACK, a local company in Korea.





STACK UP	
THICKNESS	MATERIAL
150um	STIFFENER
25um	COVERLAY ADHESIVE
35um	COPPER
50um	POLYIMIDE CORE
35um	COPPER
25um	COVERLAY ADHESIVE
13um	COVERLAY

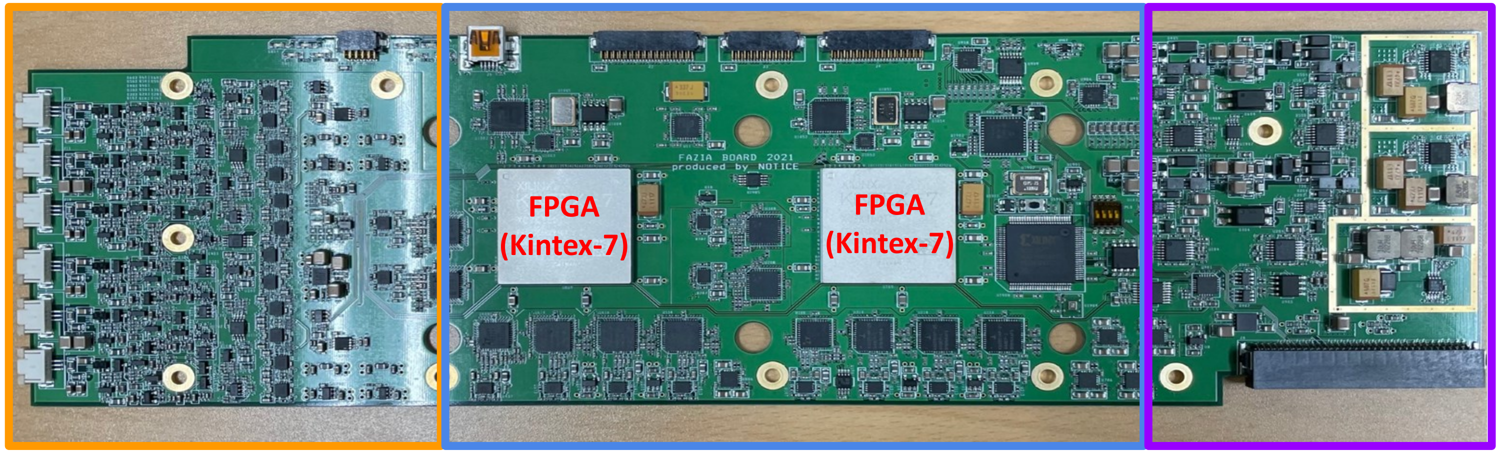
TOTAL THICKNESS 0.310mm ± 0.010mm



New front-end electronics cards

- Two prototype FEE cards have been produced by the Korean vendor, NOTICE.
  - We started with the original schematics for the FEB design provided by FAZIA.
  - Out-of-dated digital parts are replaced, e.g., Vertex-5 → KINTEX-7 for FPGA.
  - Development of the new VHDL code for new FPGA chips
  - Performance test at GANIL and INFN-Firenze: No major issue
  - The two updated FEE cards produced were tested with good results during the beam test at CNAO in Italy this year and were validated for further production.
  - Currently, FEBs for four blocks are in production.

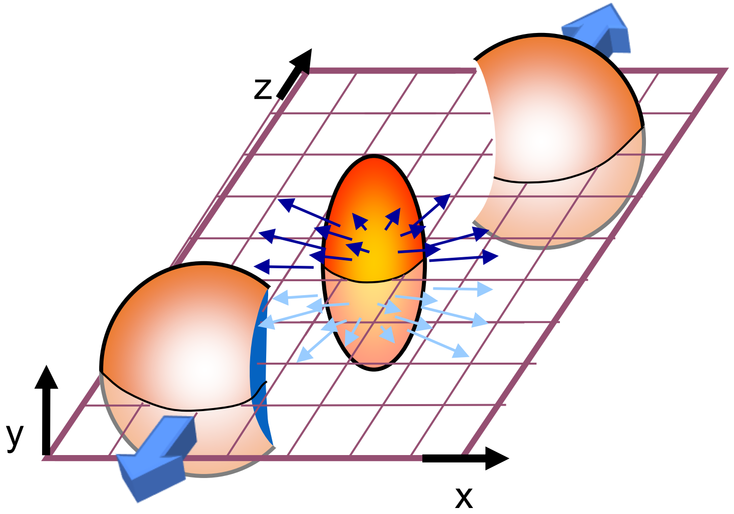
Prototype FEE card



- **Analog part**: To amplify analog signals from the detector
- **Digital part**: Signal processing (analog to digital conversion)
- **Conversion part**: Power distribution Application of bias voltage

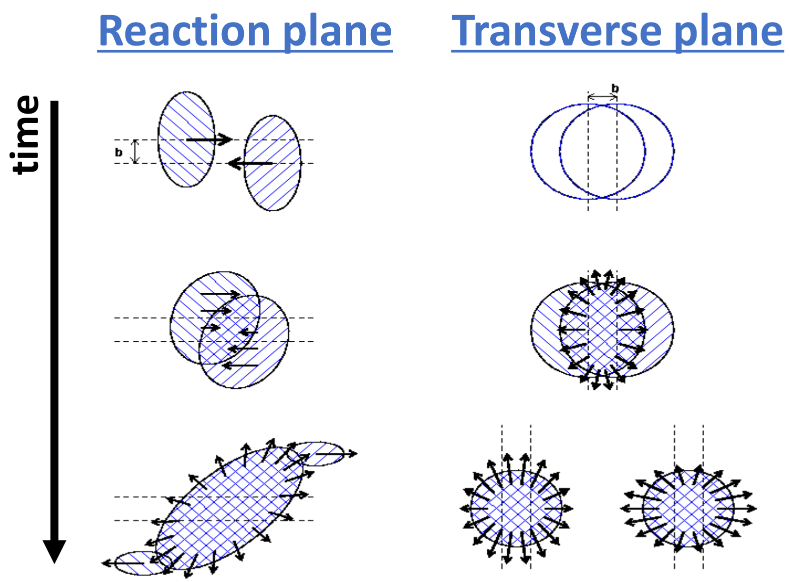
Analysis of collective flow

- Purpose
  - Investigation of the isospin dependence of the collective flow
- Data sets
  - INDRA: $^{129,124}Xe + ^{124,112}Sn$ @ 100 AMeV
  - FAZIA+INDRA: $^{58,64}Ni + ^{58,64}Ni$ @ 32 and 52 AMeV



$$\frac{d^3N}{p_t dp_t dy d\phi} \propto 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots$$

where $\phi \equiv \phi_{meas} - \Psi_R$



Directed (Sideward) flow

$v_1 < 0 \quad v_1 > 0$

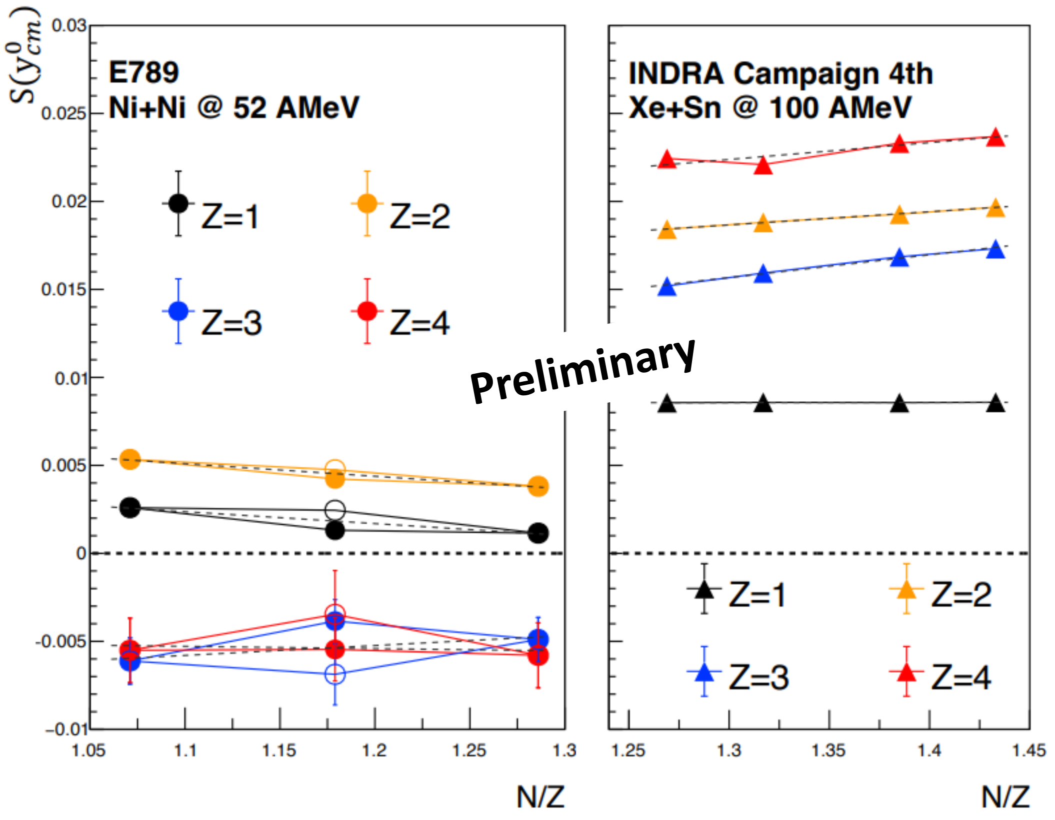
$v_1 = \langle p_x / p_t \rangle$

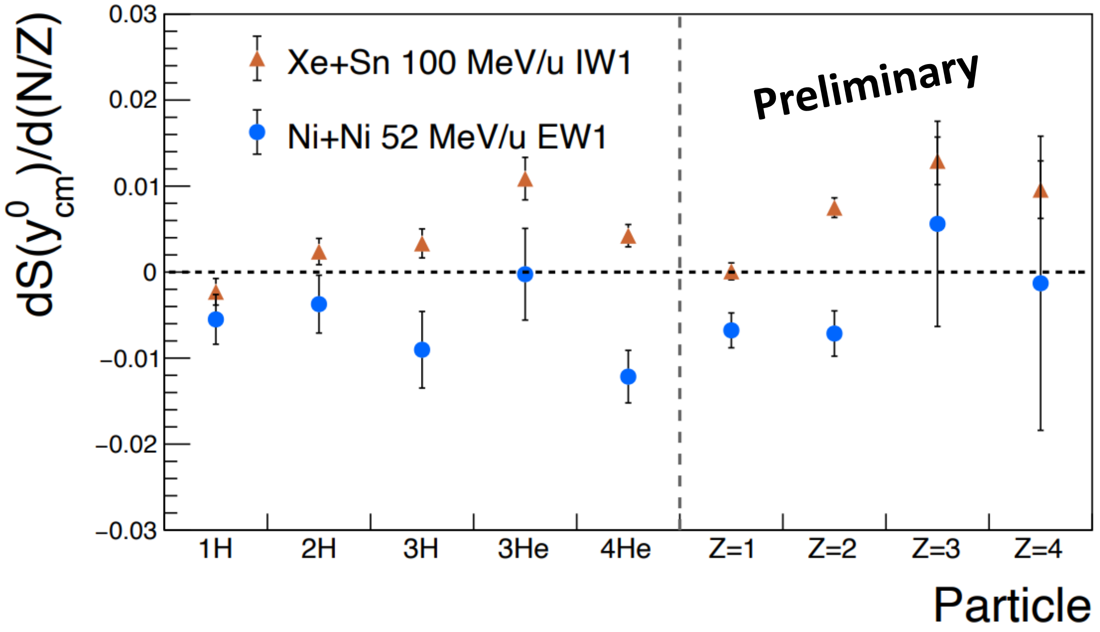
Elliptic flow

$v_2 < 0 \quad v_2 > 0$

$v_2 = \langle (p_x^2 - p_y^2)/p_t^2 \rangle$

Directed flow





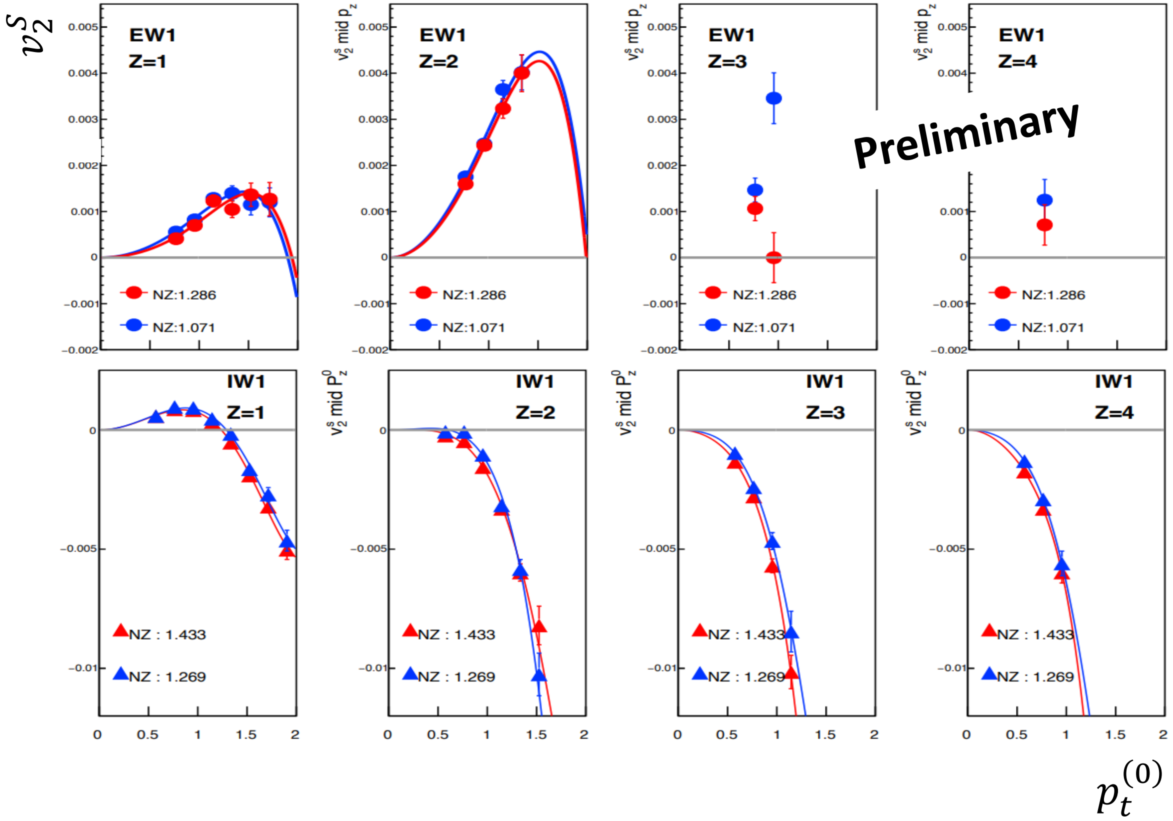
$$S(y^0_{cm}) \equiv \left. dv^S_1/dy^0_{cm}\right|_{|y^0_{cm}|<0.4}$$

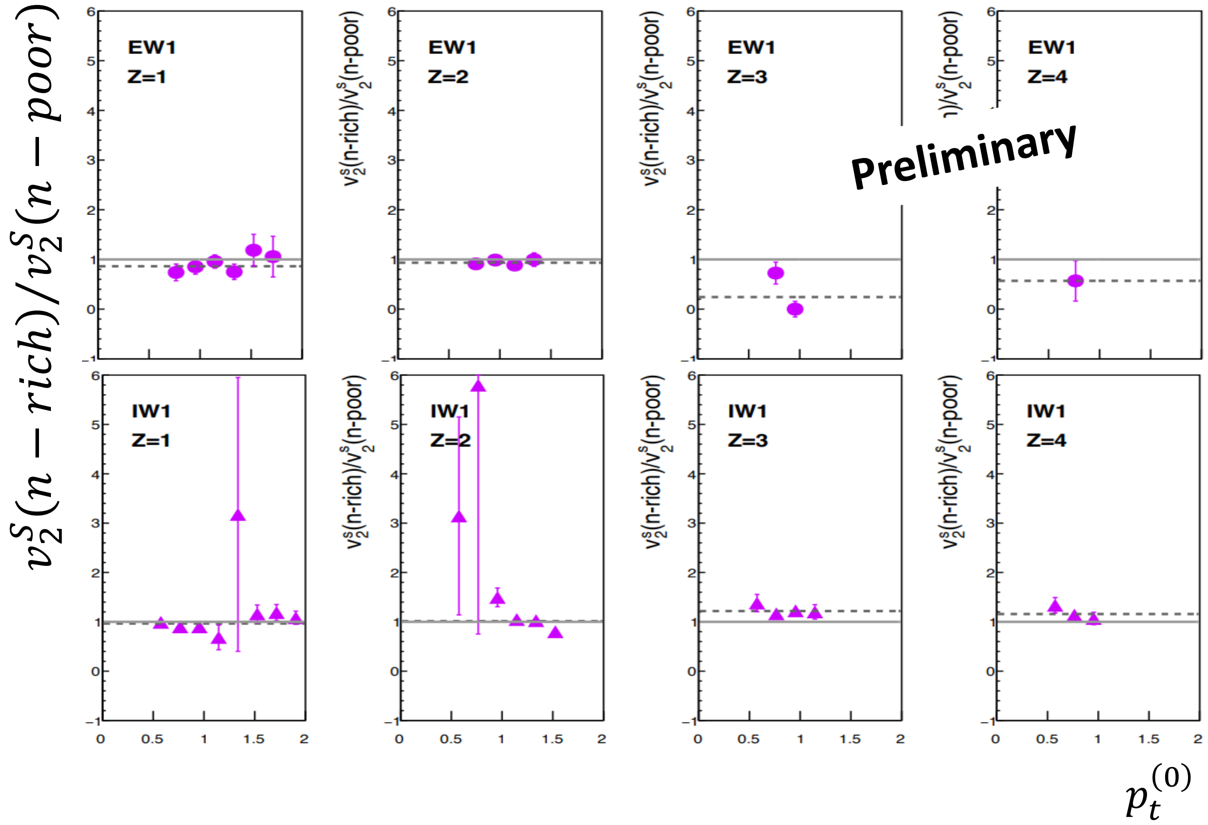
$$v^S_1 \equiv v_1 \cdot \left\langle p_t^{(0)} \right\rangle / \left(A_P^{1/3} + A_T^{1/3}\right)$$

$$p_t^{(0)} \equiv (p_t^{cm}/A)\,(A_P + A_T)/2p^{cm}_{beam}$$

- ☐ Directed flow parameters for heavy system show larger sensitivity to the isospin composition (N/Z) of projectile and target.

Elliptic flow





$$v_2^S \equiv \; v_2 \cdot \left\langle p_t^{(0)} \right\rangle / \left(A_P^{1/3} + A_T^{1/3} \right) \Big|_{|p_z^{(0)}|<0.4}$$

$$p_z^{(0)} \equiv p_z^{cm} / p_{beam}^{cm}$$

- ☐ Elliptic flow parameter does not show sensitivity to the isospin composition (N/Z) of projectile and target.

Summary

- The French-Korean Collaboration is well underway in FAZIA for the detector development and the data analysis.
  - We have produced the prototype Si sensors with the thickness of 115 and 750 μm and tested various characteristics of them.
    - The 750 μm thick Si detectors were successfully used during E818 at GANIL (the second INDRA-FAZIA campaign) and brought very good results.
  - We have successfully developed the new front-end electronics board.
    - The two updated FEE cards produced in Korea were tested during the beam test at CNAO in Italy this year and were validated for further production.
  - The data analysis on the collective flow is in good progress.
- Plan for 2024-2025
  - Construction of at least one FAZIA block in Korea
    - Eventually, we plan to build four blocks for the next 2-3 years mainly with Si and FEE cards from Korea and some of the mechanical parts from Europe.
  - Mass production of FEE cards for four blocks
  - Publication of the data analysis results for collective flow

Merci Beaucoup.

どうもありがとうございます.

감사합니다.

Thank you very much.