Large-acceptance isotope identification array FAZIA: Status and R&D activities for upgrade

MinJung Kweon

On behalf of the FAZIA collaboration

Inha University

2022. 10. 7, EMIS XIX

The FAZIA project

Forward A and Z Identification Array

International collaboration (MoU 2018-2022)

- 5 countries (Italy, France, Poland, Spain, Korea)
- ~30 physicists & ~10 students

Scientific goal

- Detailed understanding of the nuclear Equation of State (EOS) and constraining the nuclear symmetry energy for both microscopic (nuclei) and macroscopic (neutron stars) objects

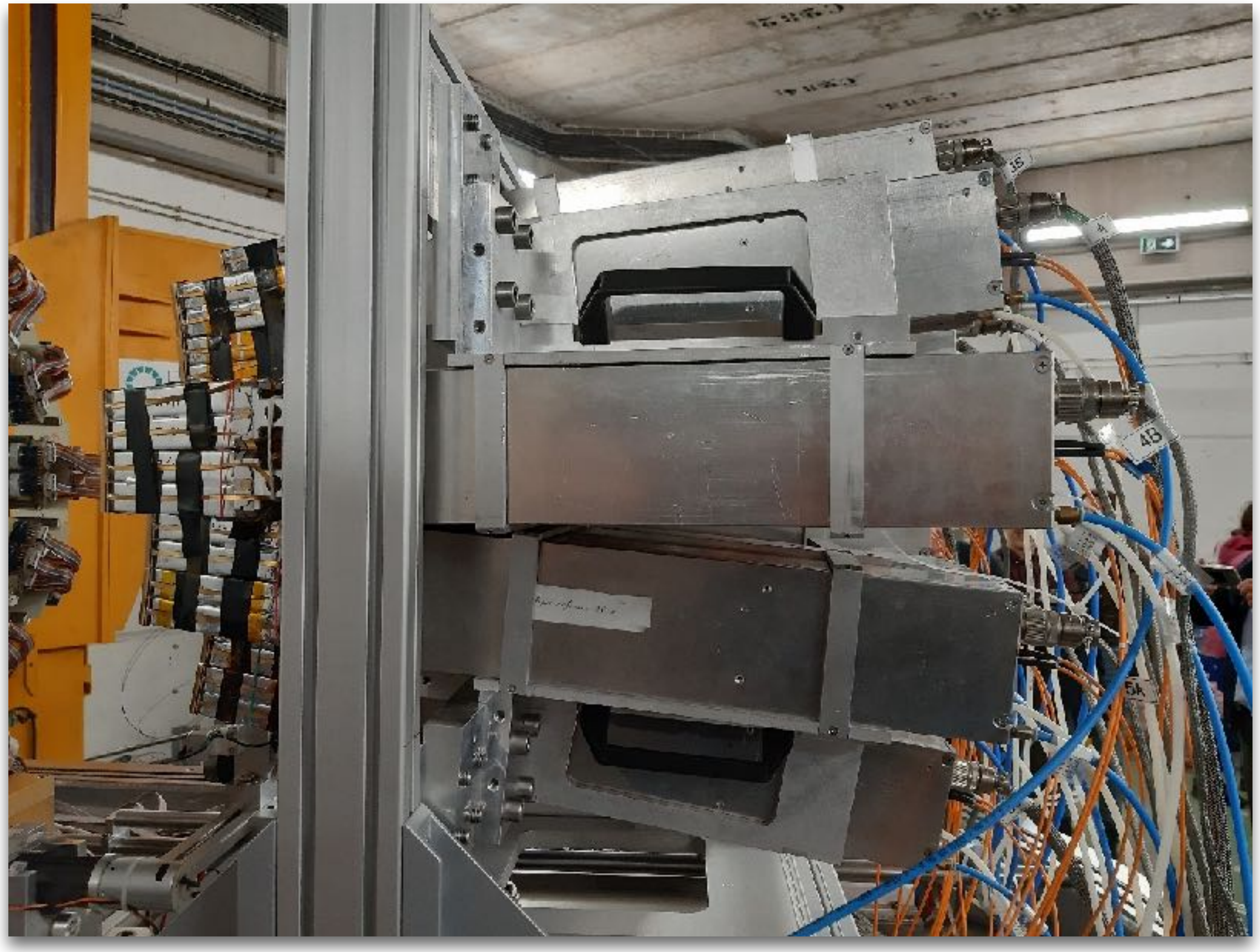
Technical goal

- Improving Z and A identification on a large scale for isospin physics
- “Lower” energy identification thresholds (by means of pulse shape analysis)
- Modular, versatile and transportable apparatus

Main phases

- R&D on detectors and electronics (2002-2012): finished
- Commissioning phase (2013-2018): finished
- Construction of a demonstrator (12 blocks, with 16 telescopes per block): finished
- Experiments with stable and unstable heavy-ion beams (2019 ~): ongoing
- Feasibility study of the upgrade: ongoing

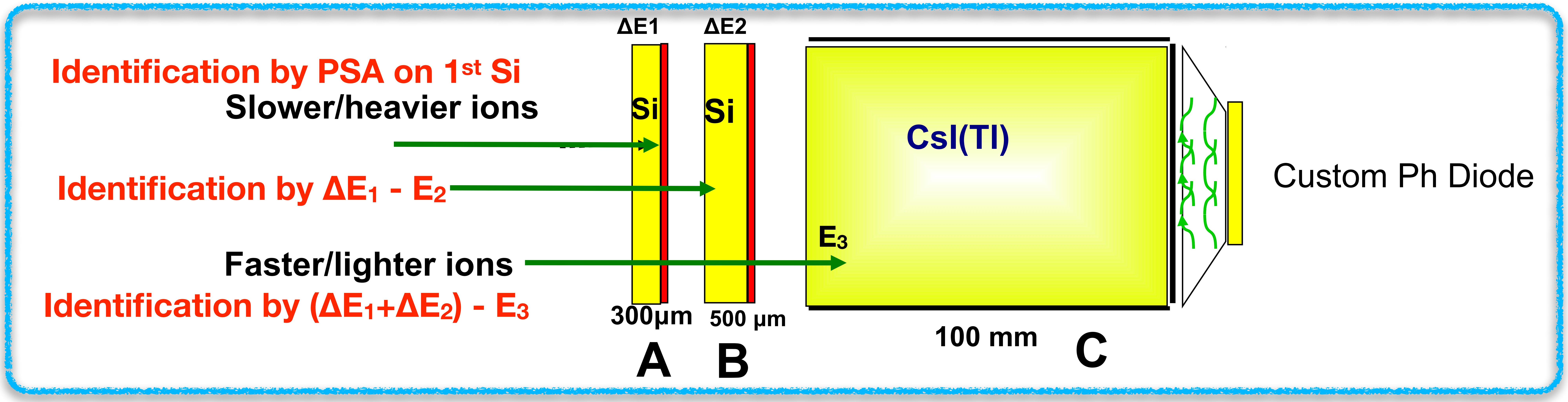
FAZIA apparatus



12 blocks, 192 telescopes Si-Si-CsI

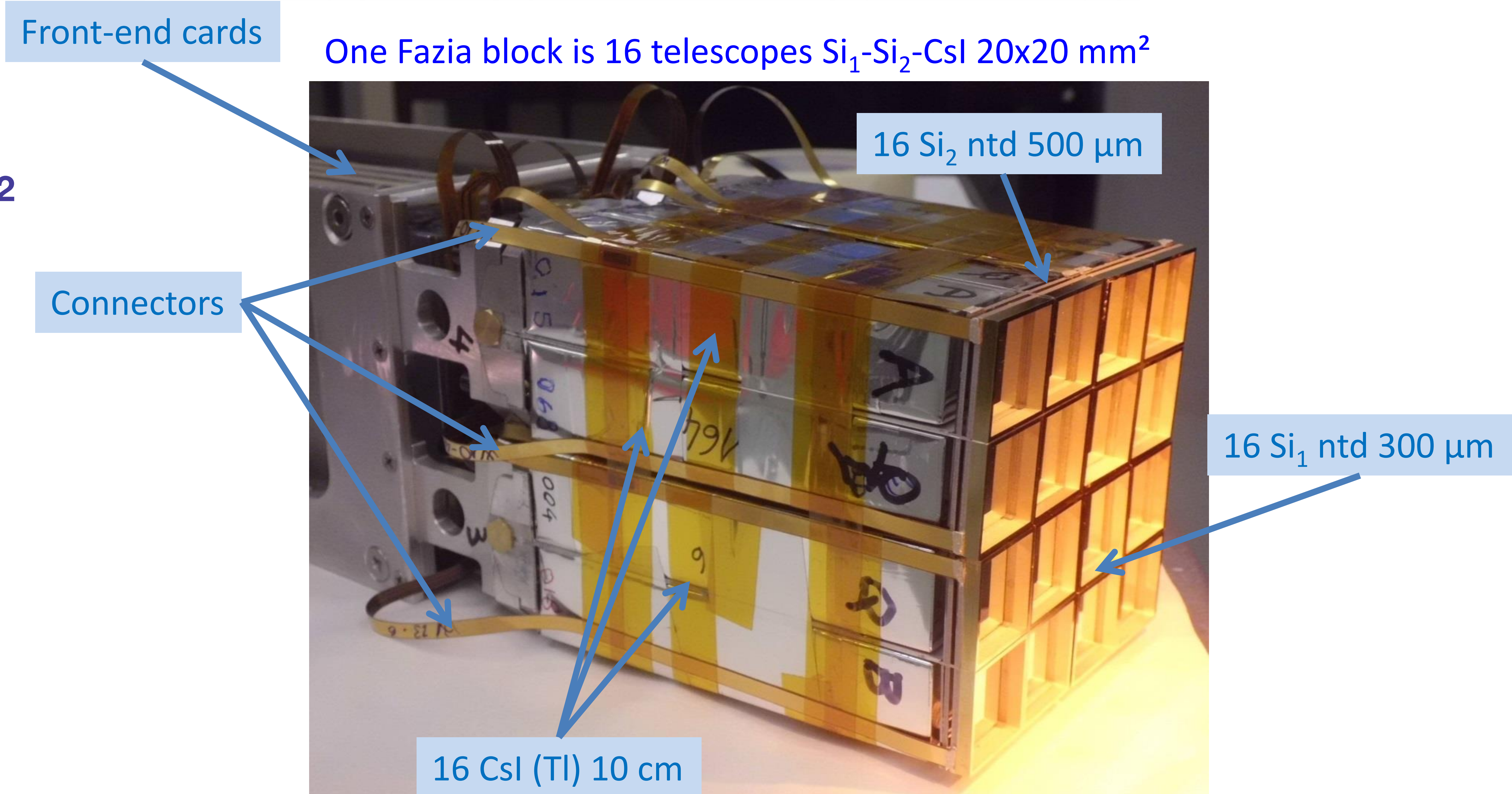
- Wall configuration at a distance of one meter from the target
- Covering the forward polar angles (1.4°< θ < 12.6°)

The FAZIA telescope



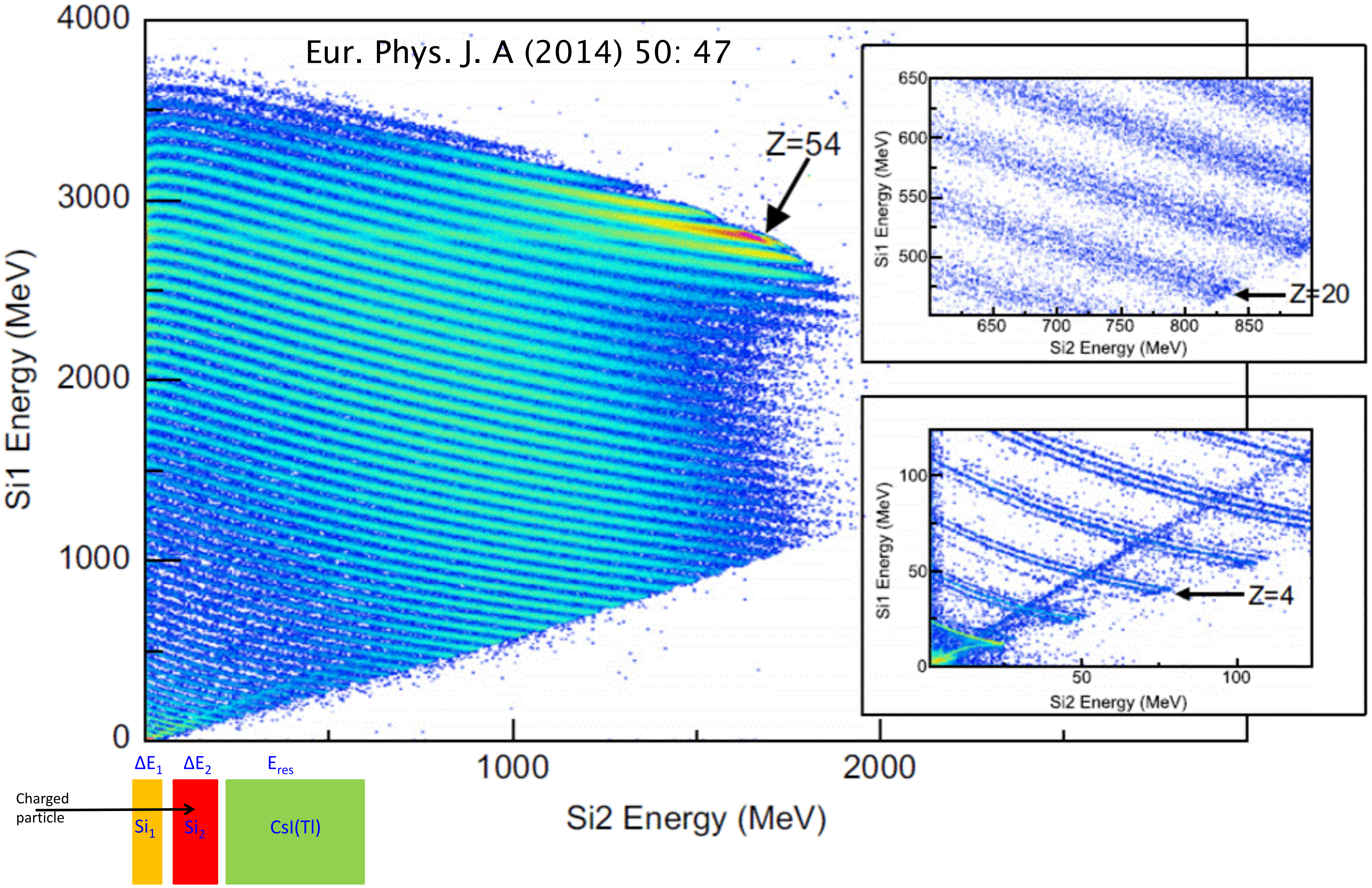
One FAZIA block consists of 16 Si1 + Si2 + CsI telescopes with a cross-sectional area of 2 x 2 cm²

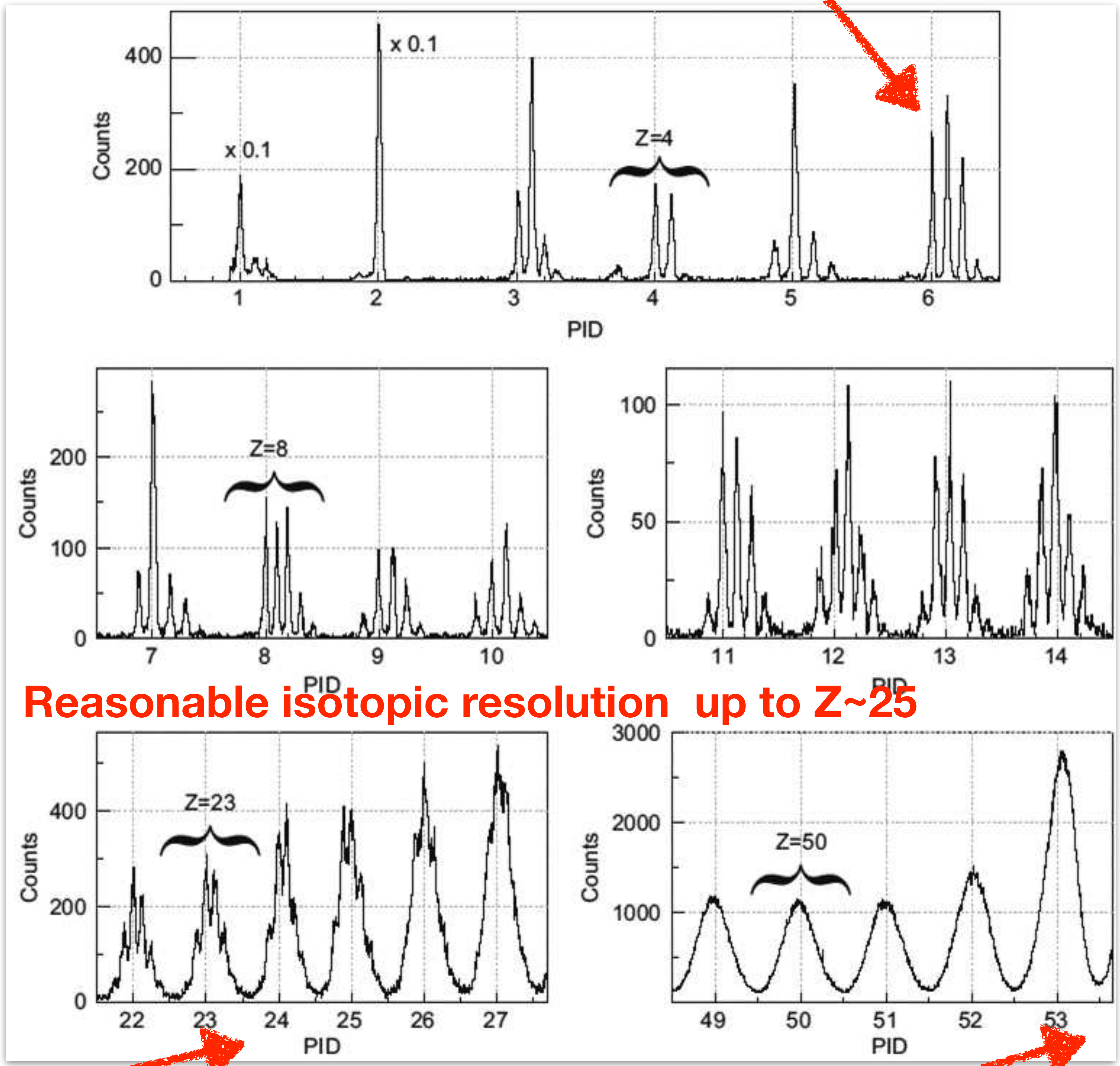
- Si1 (nTD): 300 μm thick
- Si2 (nTD): 500 μm thick
- CsI: 10 cm thick, photodiode readout
- Dedicated digital electronics with optical fiber outputs
- 8 FEE cards cooled under vacuum



FAZIA PID performance

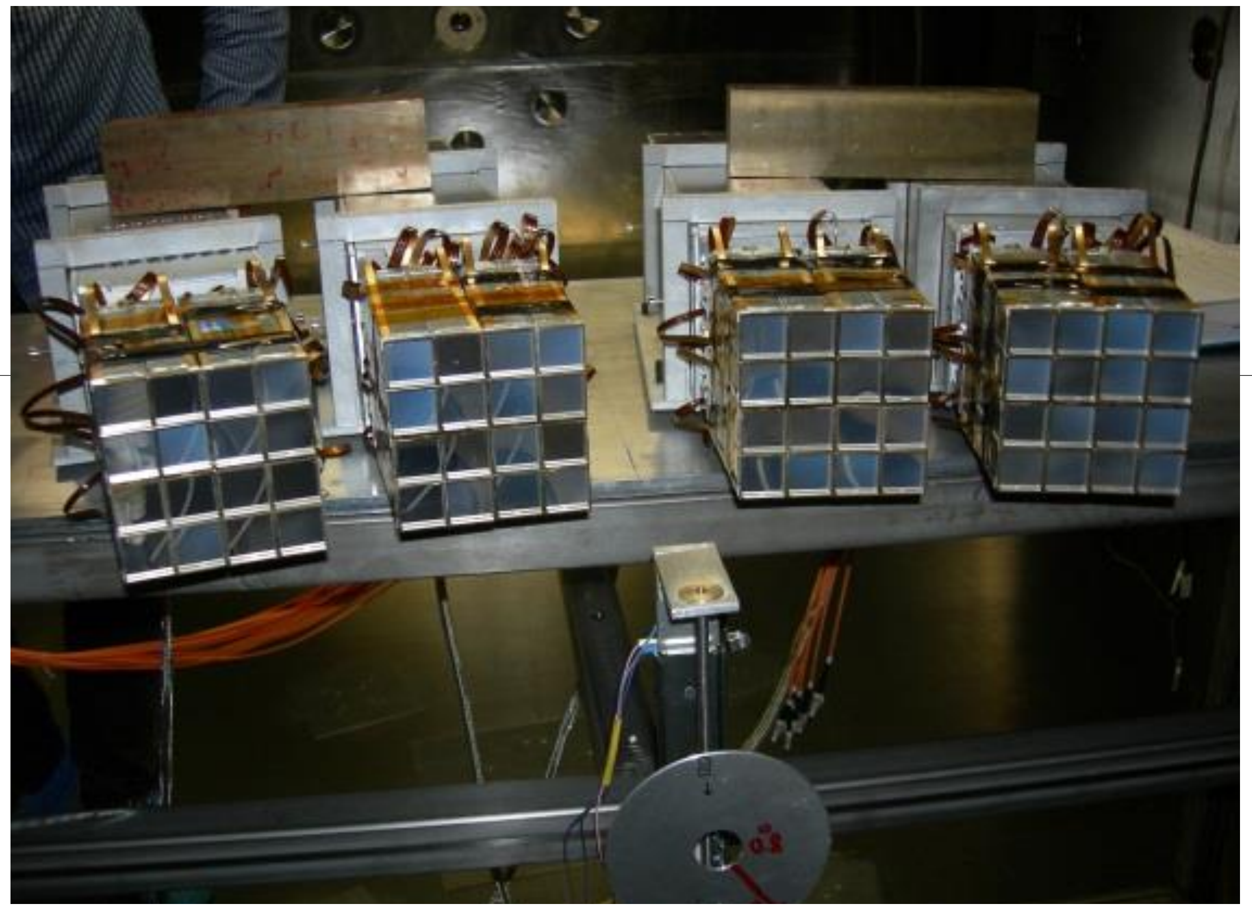
For Z = 6
- charge identification from 2 MeV/u
- isotopic discrimination from 5 MeV/u





- During the R&D phase, the ΔE-E charge identification capability has been successfully tested up to Z ~ 54
- Isotopic discrimination has been achieved up to Z ~ 25 with the ΔE-E technique and up to Z ~ 20 with PSA in silicon

FAZIA commissioning phase



FAZIA commissioning phase at LNS Catania 2013-2018

1st physics oriented experiment

FAZIA May 2013
1 block + telescopini
84Kr at 35A MeV

FAZIA December 2014
2 blocks horizontal plane 10 UTs
^{84}Kr + ^{58}Ni, ^{93}Nb & $^{112\text{-}124}$Sn at 24.75 A MeV

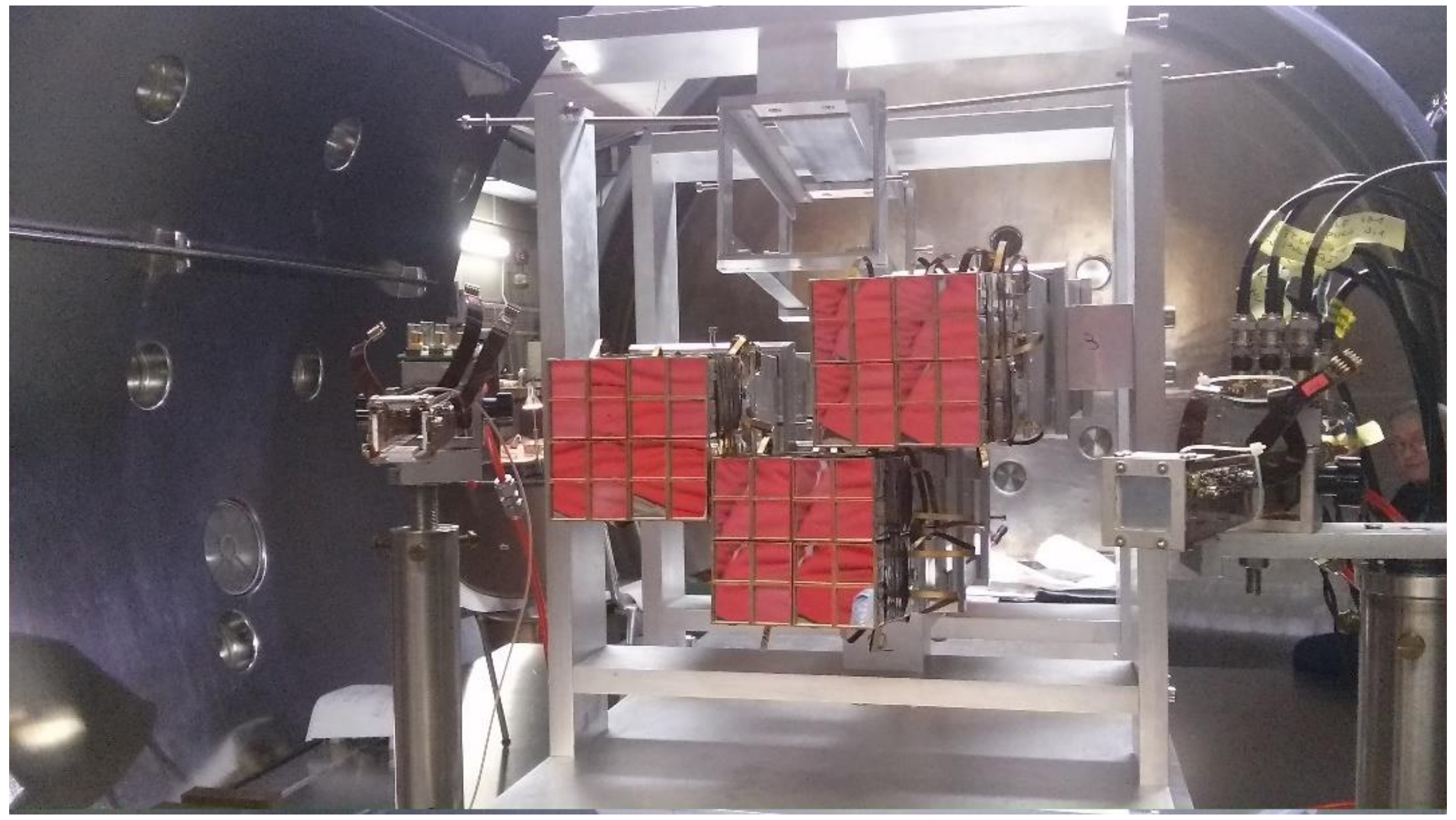
ISOFAZIA June 2015
4 blocks horizontal plane 25 UTs
^{40}Ar at 35 A MeV & ^{80}Kr + $^{40\text{-}48}$Ca at 35 A MeV

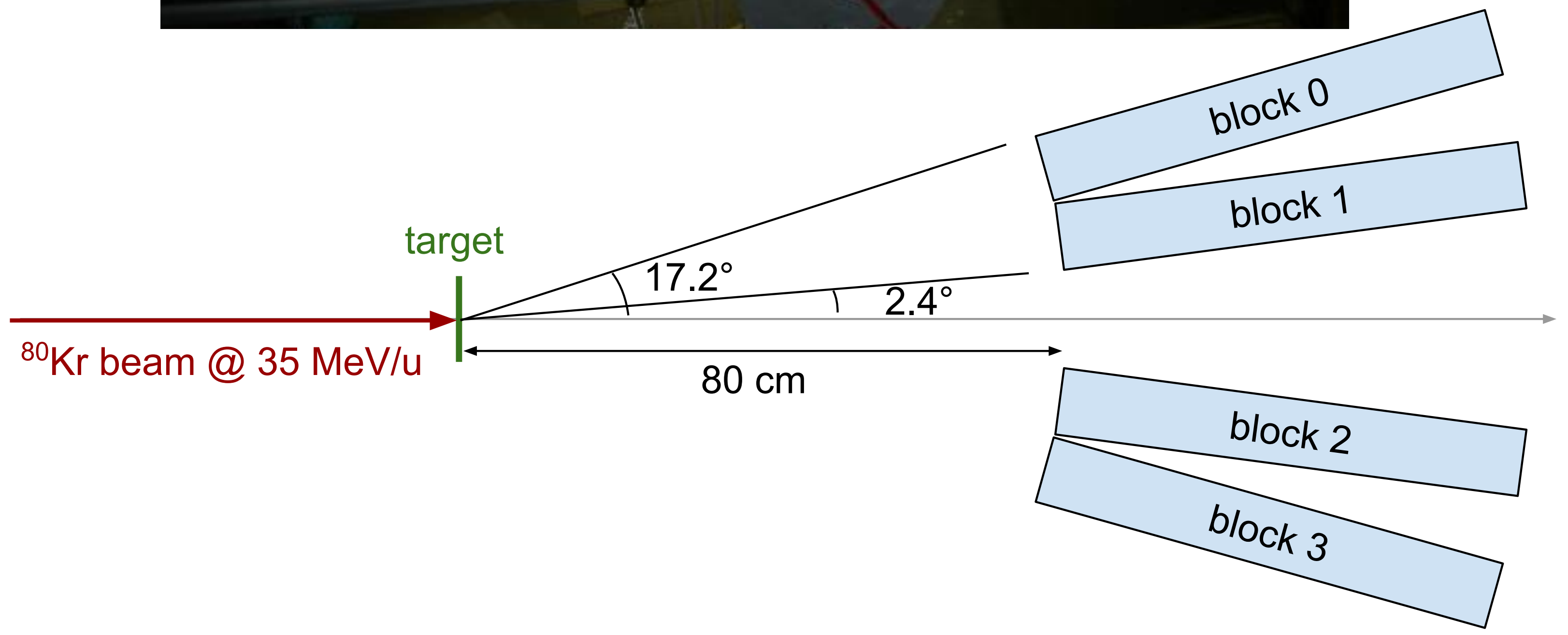
FAZIASYM December 2015
4 blocks wall configuration
$^{40\text{-}48}$Ca + $^{40\text{-}48}$Ca at 35 A MeV

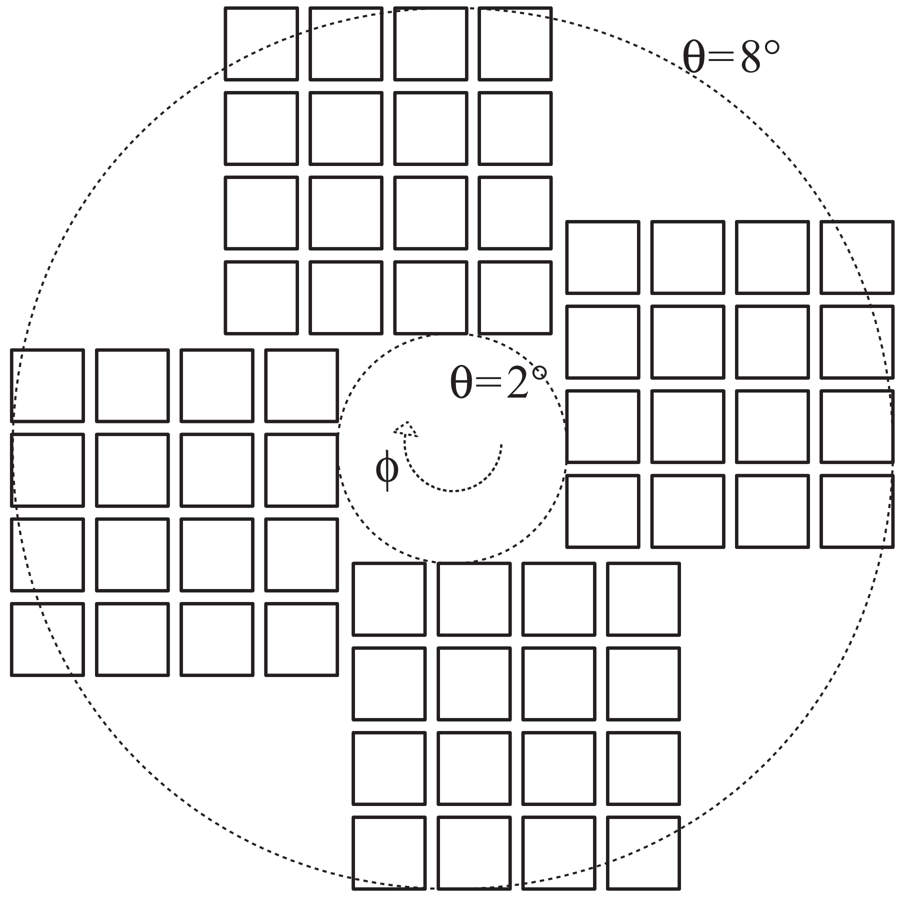
FAZIACOR March 2017
4 blocks wall configuration
^{20}Ne & ^{32}S + ^{12}C at 25 & 50 A MeV

FAZIAPRE test October 2017 experiments in February & May 2018
4 blocks wall configuration, plus 2 lateral blocks
$^{40\text{-}48}$Ca + ^{12}C at 25 & 40 A MeV + few runs with ^{27}Al & ^{40}Ca

FAZIAZERO July 2018
4 blocks wall configuration, plus 1 lateral bloc & one at 0°
^{12}C + ^{12}C & (CH_2)n at 62 & 80 A MeV







Courtesy of Nicolas Le Neindre, LPC CAEN

FAZIA commissioning phase: stable ^{84}Kr beam

FAZIA commissioning phase at LNS Catania 2013-2018

FAZIA May 2013
1 block + telescopini
84Kr at 35A MeV

FAZIA December 2014
2 blocks horizontal plane 10 UTs
^{84}Kr + ^{58}Ni, ^{93}Nb & $^{112-124}$Sn at 24.75 A MeV

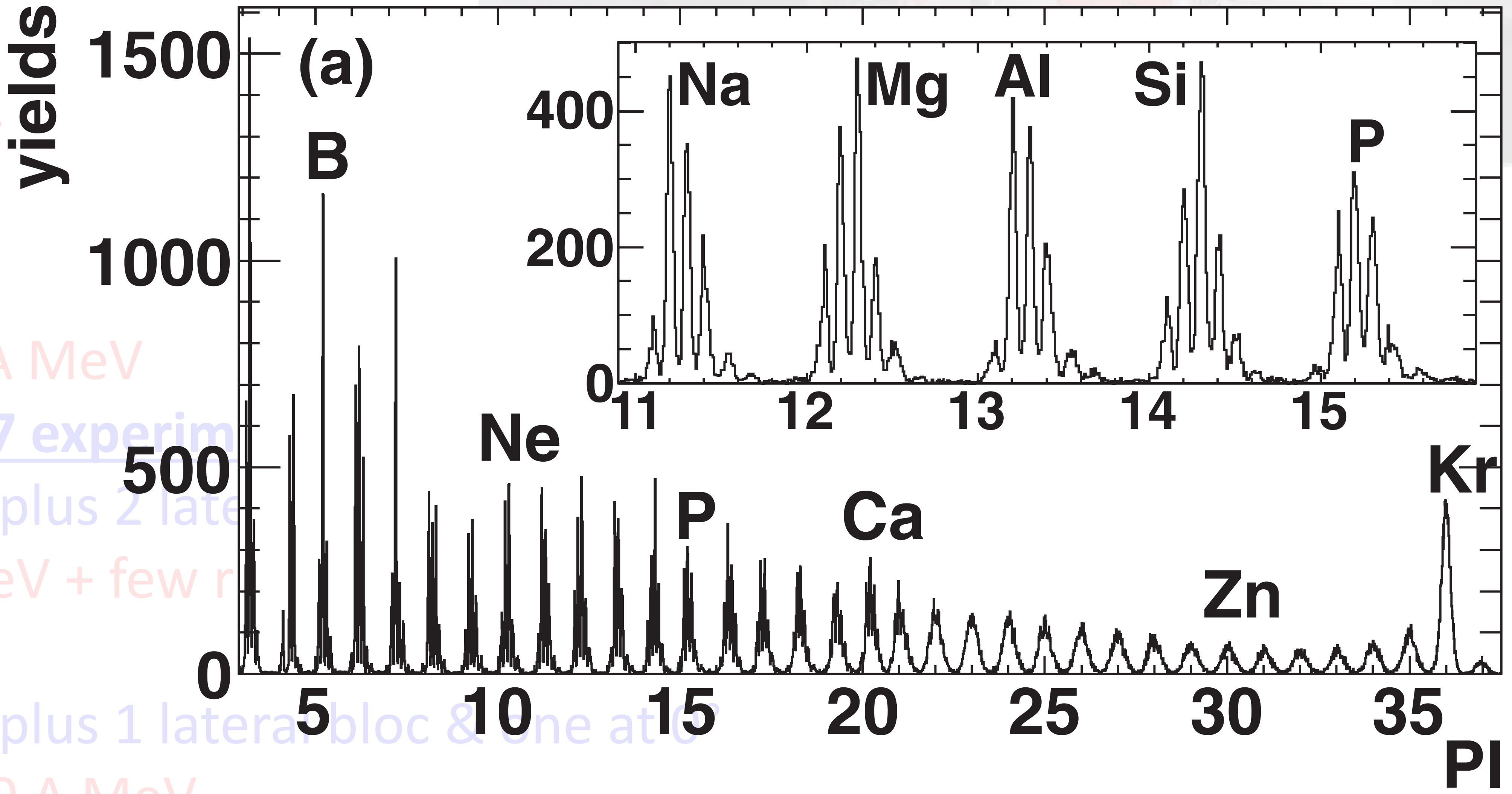
ONE block!
called test run!

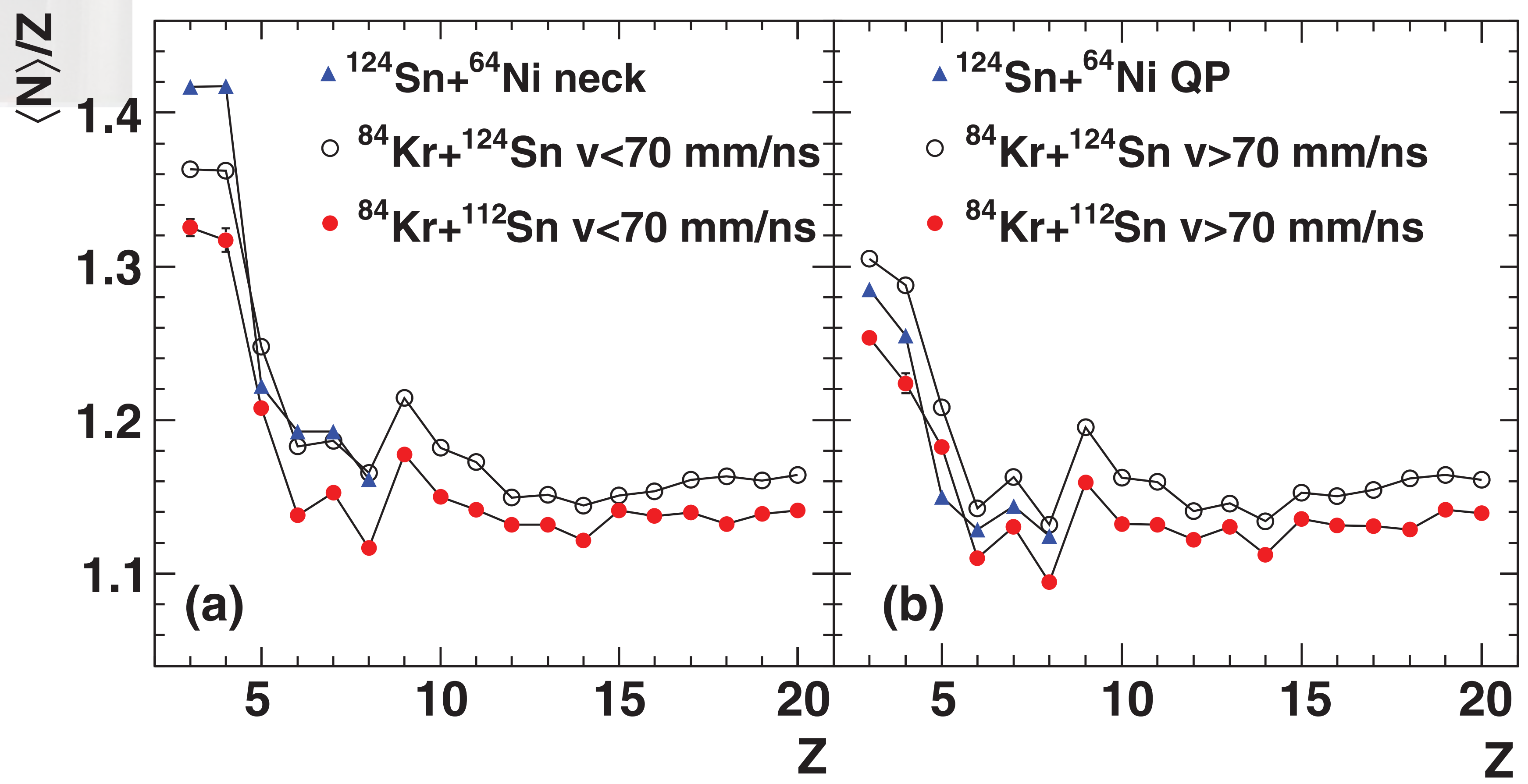
4 blocks horizontal plane 25 UTs
^{40}Ar at 35 A MeV & ^{80}Kr + $^{40-48}$Ca at 35 A MeV
FAZIASYM December 2015
4 blocks wall configuration
$^{40-48}$Ca + $^{40-48}$Ca at 35 A MeV
FAZIACOR March 2017
4 blocks wall configuration
^{20}Ne & ^{32}S + ^{12}C at 25 & 50 A MeV
FAZIAPRE test October 2017 experim…
4 blocks wall configuration, plus 2 late…
$^{40-48}$Ca + ^{12}C at 25 & 40 A MeV + few …
FAZIAZERO July 2018
4 blocks wall configuration, plus 1 lateral bloc & one at…
^{12}C + ^{12}C & (CH…)n at 62 & 80 A MeV

PHYSICAL REVIEW C **87**, 054607 (2013)

Isospin transport in ^{84}Kr + ^{112,124}Sn collisions at Fermi energies

Isotopically resolved fragments with $Z \lesssim 20$ have been studied with a high-resolution telescope in a test run for the FAZIA Collaboration. The fragments were produced by the collision of a ^{84}Kr beam at 35 MeV/nucleon with a neutron-rich (^{124}Sn) and a neutron-poor (^{112}Sn) target. The fragments, detected close to the grazing angle, are mainly emitted from the phase-space region of the projectile. The fragment isotopic content clearly depends on the neutron richness of the target and this is direct evidence of isospin diffusion between projectile and target. The observed enhanced neutron richness of light fragments emitted from the phase-space region close to the center of mass of the system can be interpreted as an effect of isospin drift in the diluted neck region.





identified fragments (Z >= 3) that are stopped in the second silicon layer or in the CsI(Tl), isotope resolution up to Z ~ 20

FAZIA commissioning phase: Ca isotope beams

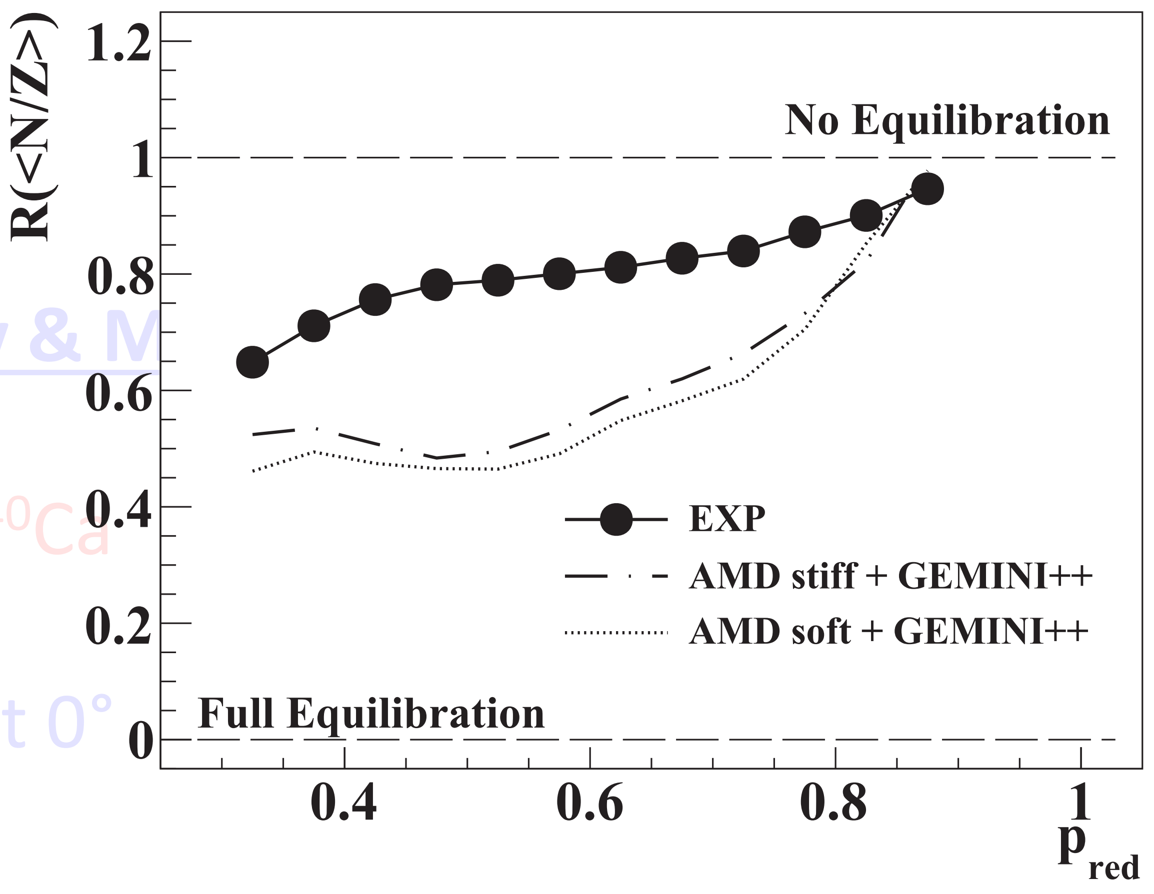
FAZIA commissioning phase at LNS Catania 2013-2018

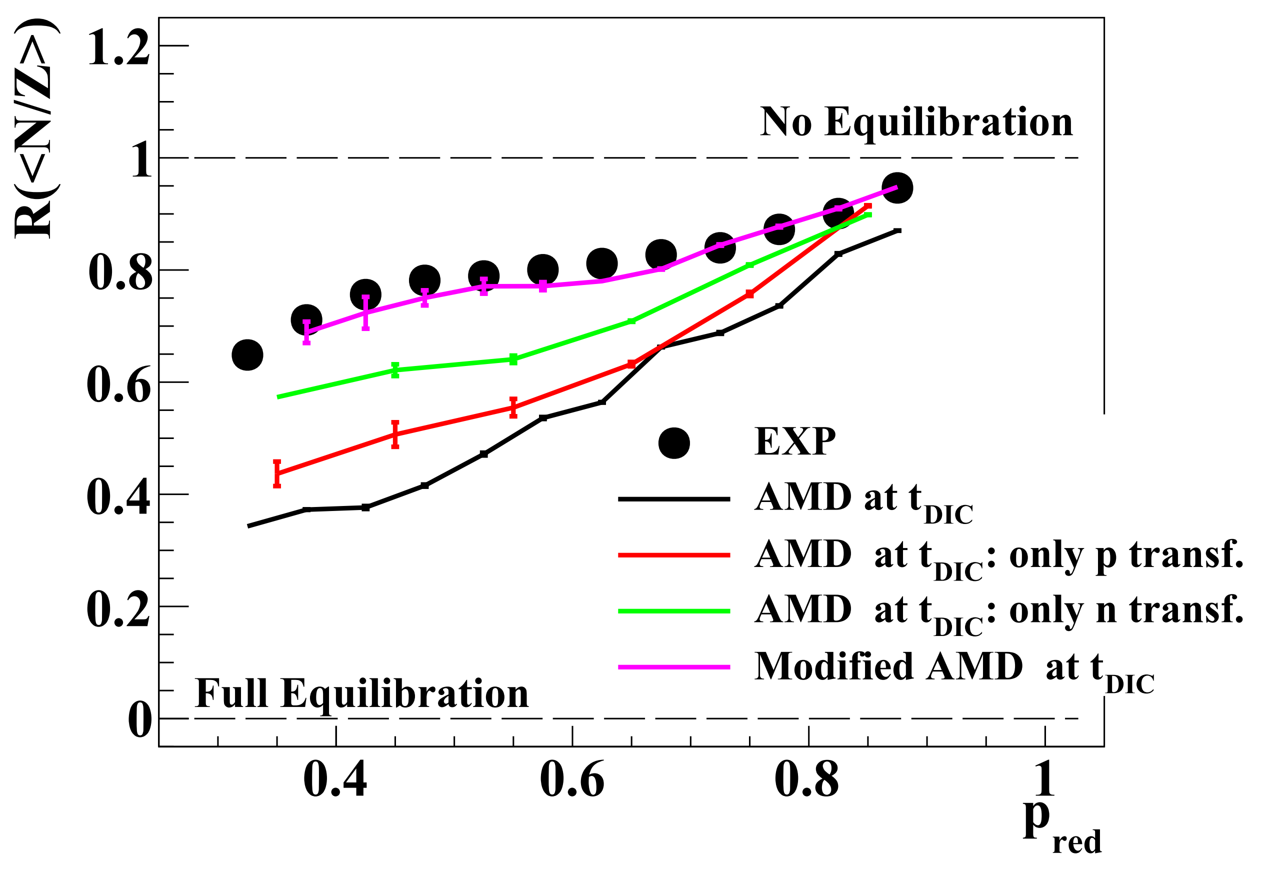
FAZIA May 2013
1 block + telescopini
84Kr at 35A MeV
FAZIA December 2014
2 blocks horizontal plane 10 UTs
^{84}Kr + ^{58}Ni, ^{93}Nb & $^{112\text{-}124}$Sn at 24.75 A MeV
ISOFAZIA June 2015
4 blocks horizontal plane 25 UTs
^{40}Ar at 35 A MeV & ^{40}Kr ... $^{40\text{-}48}$Ca at 35 A MeV
FAZIASYM December 2015
4 blocks wall configuration
$^{40\text{-}48}$Ca + $^{40\text{-}48}$Ca at 35 A MeV
FAZIACOR March 2017
4 blocks wall configuration
^{20}Ne & ^{32}S + ^{12}C at 25 & 50 A MeV
FAZIAPRE test October 2017 experiments in February & M
4 blocks wall configuration, plus 2 lateral blocks
$^{40\text{-}48}$Ca + ^{12}C at 25 & 40 A MeV + few runs with ^{27}Al & ^{40}Ca
FAZIAZERO July 2018
4 blocks wall configuration, plus 1 lateral bloc & one at 0°
^{12}C + ^{12}C & (CH_2)n at 62 & 80 A MeV

PHYSICAL REVIEW C **103**, 014605 (2021)

Isospin diffusion measurement from the direct detection of a quasiprojectile remnant

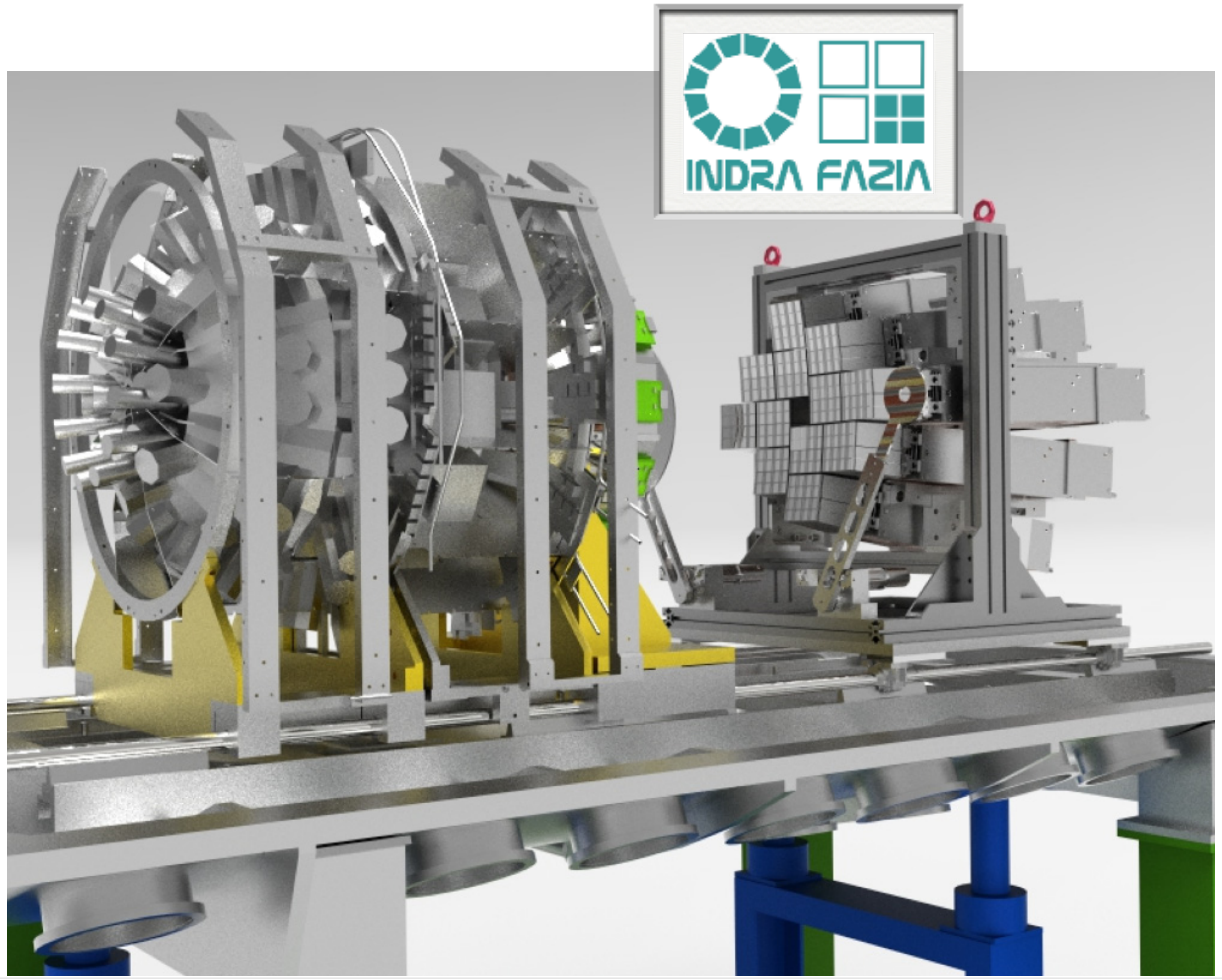
The neutron-proton (n-p) equilibration process in ^{48}Ca + ^{40}Ca at 35 MeV/nucleon bombarding energy is experimentally estimated by means of the isospin transport ratio. Experimental data are collected with a subset of the FAZIA telescope array, which permits us to determine the *Z* and *N* of detected fragments. For the first time, the quasiprojectile (QP) evaporative channel is compared with the QP breakup one in a homogeneous and consistent way, pointing to comparable n-p equilibration, which suggests a close interaction time between projectile and target independently of the exit channel. Moreover, in the QP evaporative channel n-p equilibration is compared with the prediction of the antisymmetrized molecular dynamics model coupled with the GEMINI statistical model as an afterburner, showing a higher probability of proton and neutron transfers in the simulation with respect to the experimental data.

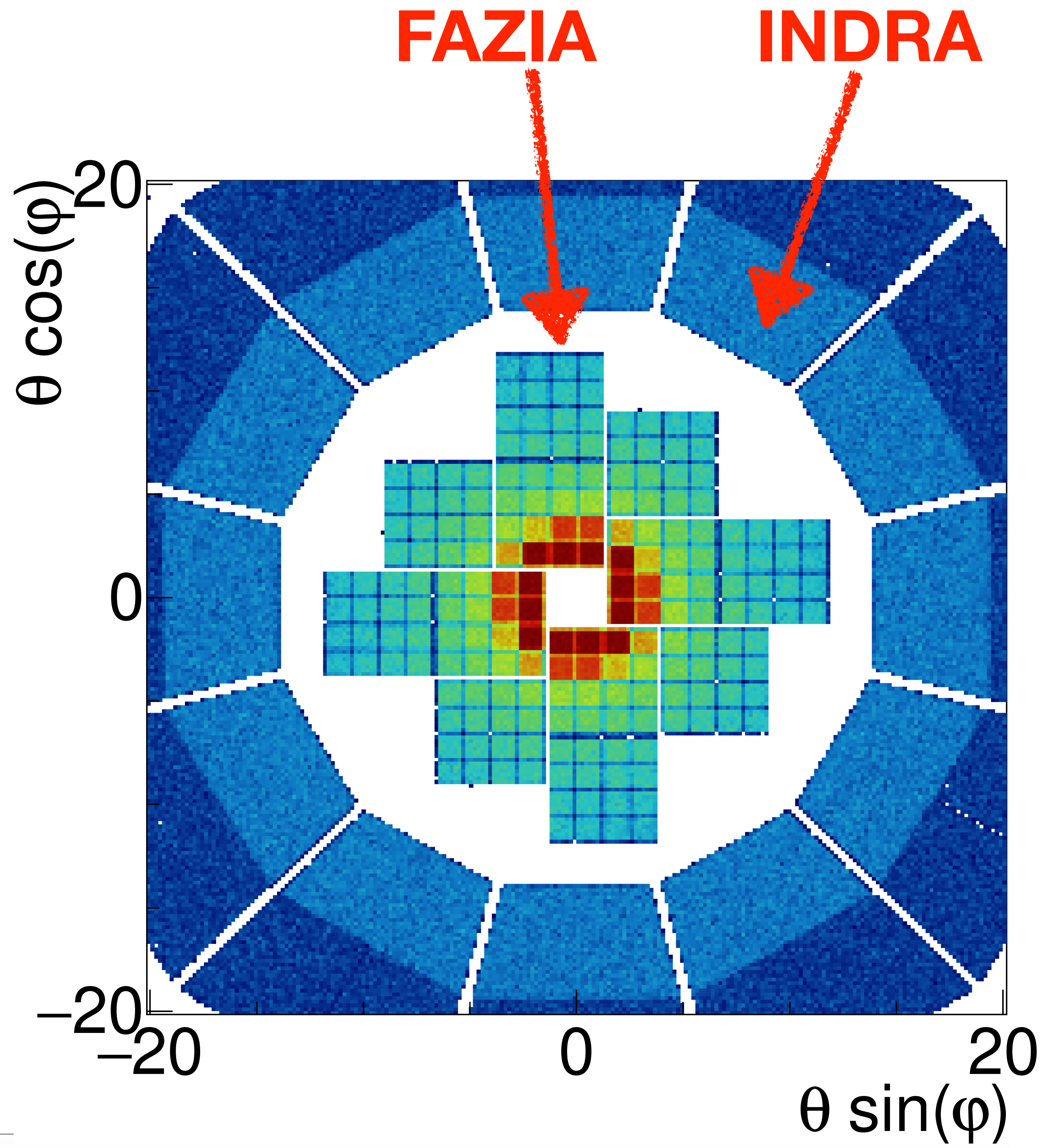




FAZIA physics phase: E789 experiment (spring , 2019)

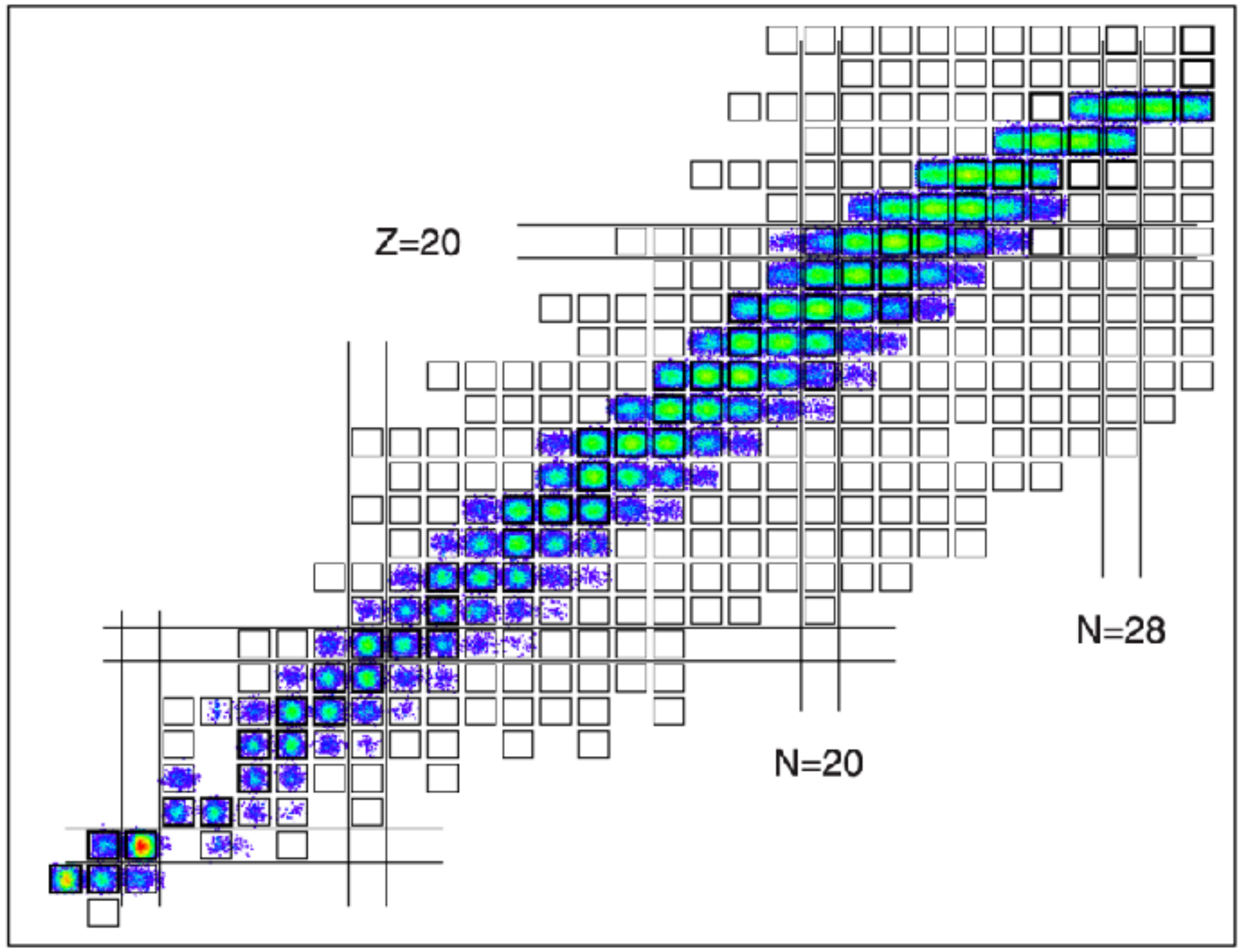
- **Study isospin transport and the density dependence of the symmetry energy**
- **Measure energy & impact parameter dependence of isospin (N/Z) transport around Fermi energy**
- **$^{58-64}$Ni + $^{64-58}$Ni @ 32 - 52 MeV/nucleon**
- **INDRA + FAZIA: 1st coupled campaign**
  - Good A & Z resolution for FAZIA → N/Z ratios
  - Full 4π angular coverage with INDRA+ FAZIA → centrality criteria





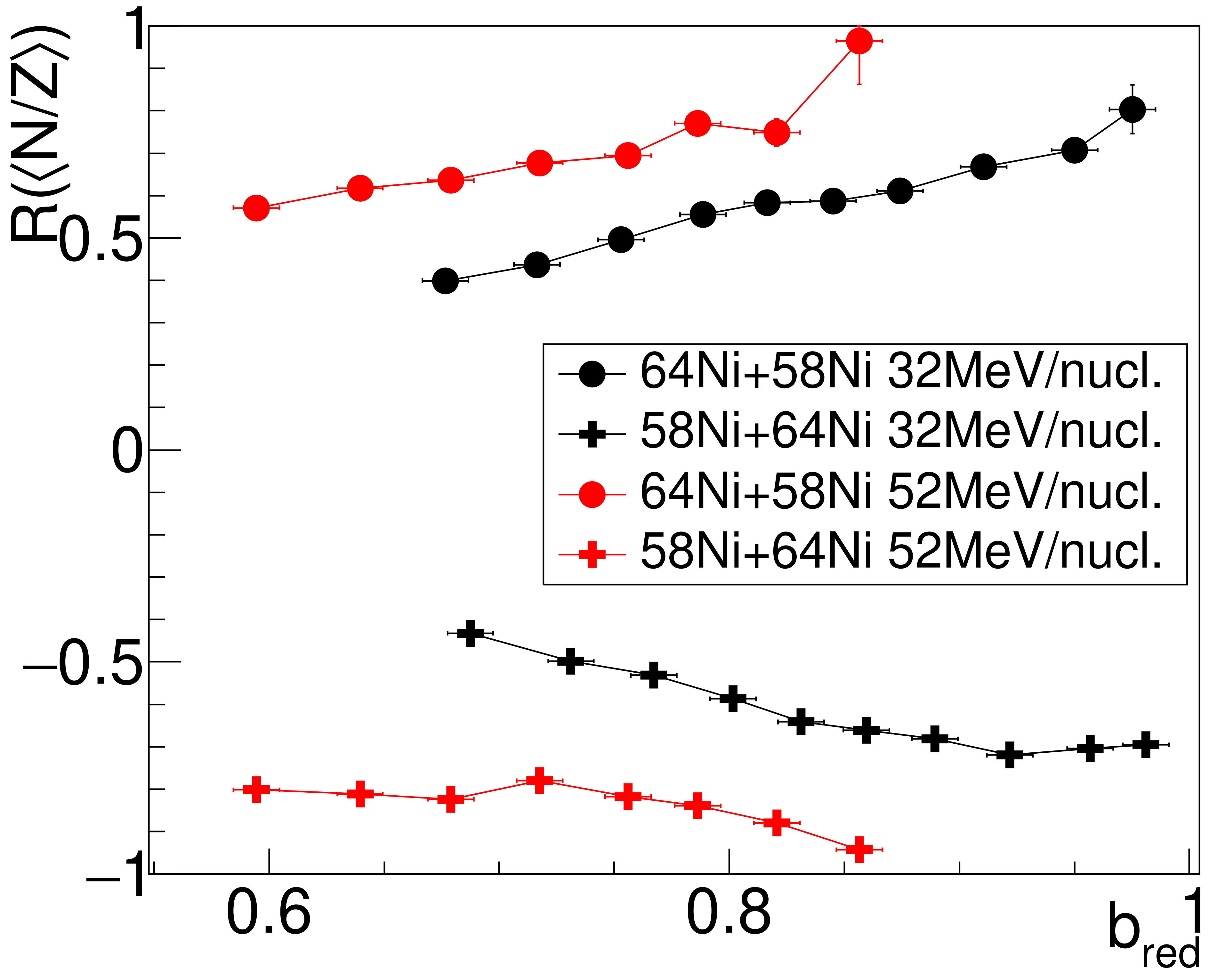
FAZIA physics phase: E789 experiment (spring , 2019)

- **Relaxation of the initial isospin imbalance with increasing centrality has been clearly evidenced.**
- **The isospin equilibration appears stronger for the reactions at 32 MeV/nucleon, as expected due to the longer projectile-target interaction time than at 52 MeV/nucleon.**



Experimental nuclear chart obtained via the Si1-Si2 ΔE-E method

PHYSICAL REVIEW C 106, 024603 (2022)

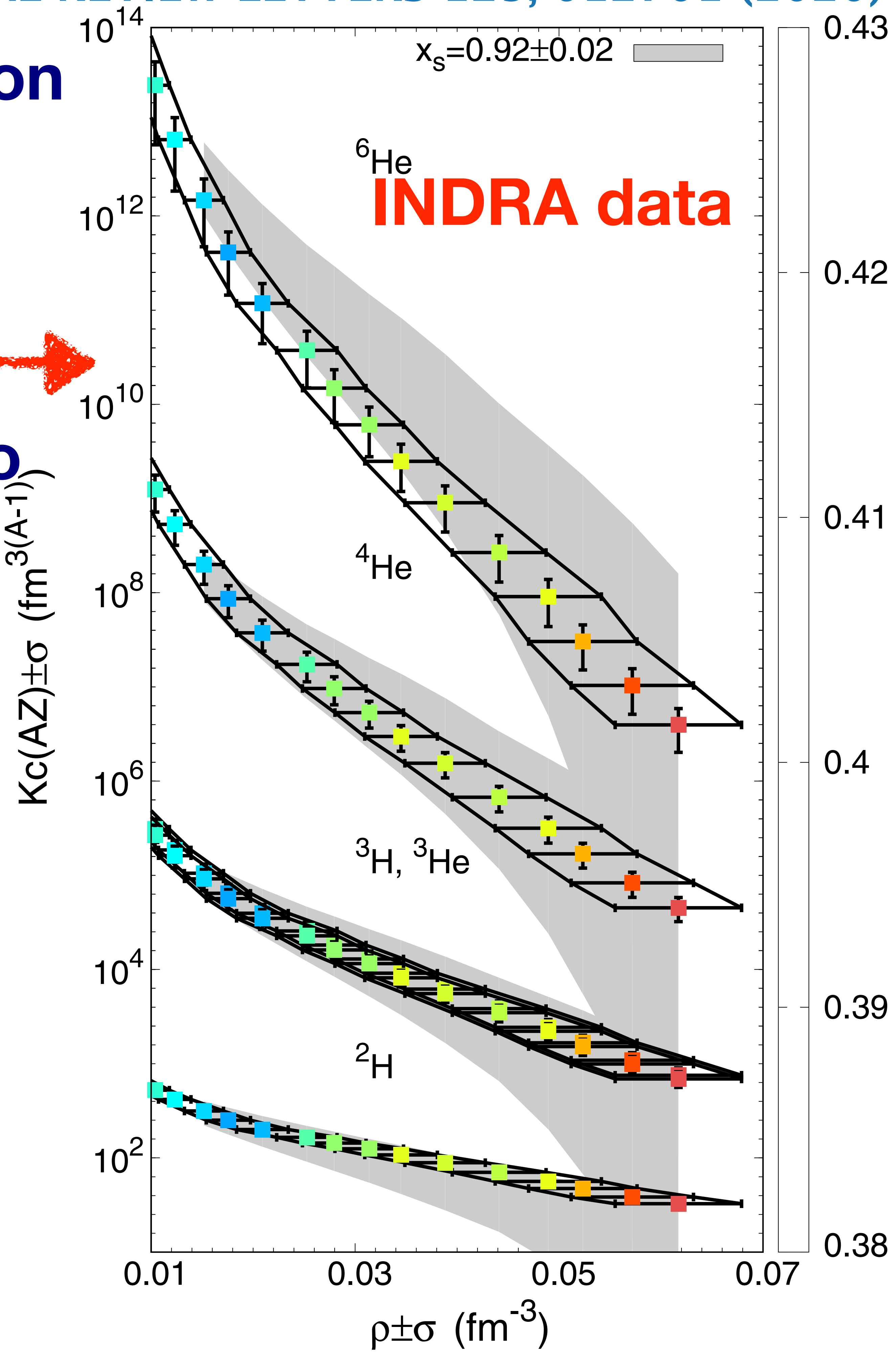


Isospin transport ratio calculated with the $\langle N\rangle/\langle Z\rangle_{cp}$ of the complex particles forward emitted with respect to the QP remnant, as a function of b_{red}

FAZIA physics phase: E818 experiment (spring , 2022)

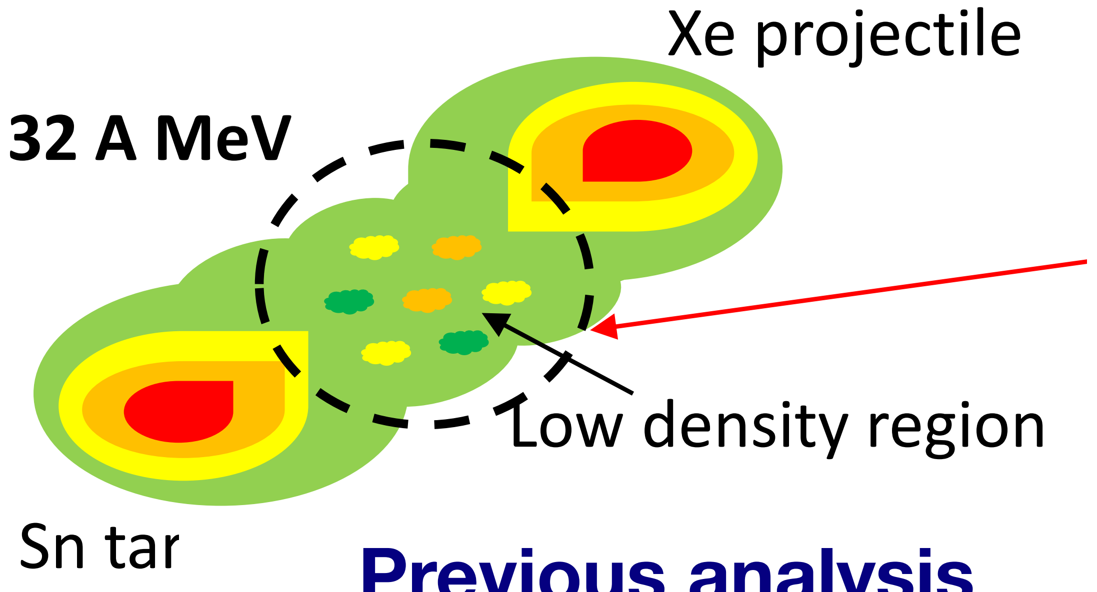
- **Extending our knowledge of warm dense nuclear matter in the low density region**
  - Modification of the ground state properties of light atomic nuclei in the nuclear and stellar medium (low density)
- **INDRA → limited set of clusters: ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}He**
- **Essential to be able to confront the calculation with a larger set of masses up to ^{12,13,14}C**
- **INDRA + FAZIA: 2nd coupled campaign**
  - Use FAZIA muti-detector (A,Z) identification up to Z~20

PHYSICAL REVIEW LETTERS 125, 012701 (2020)



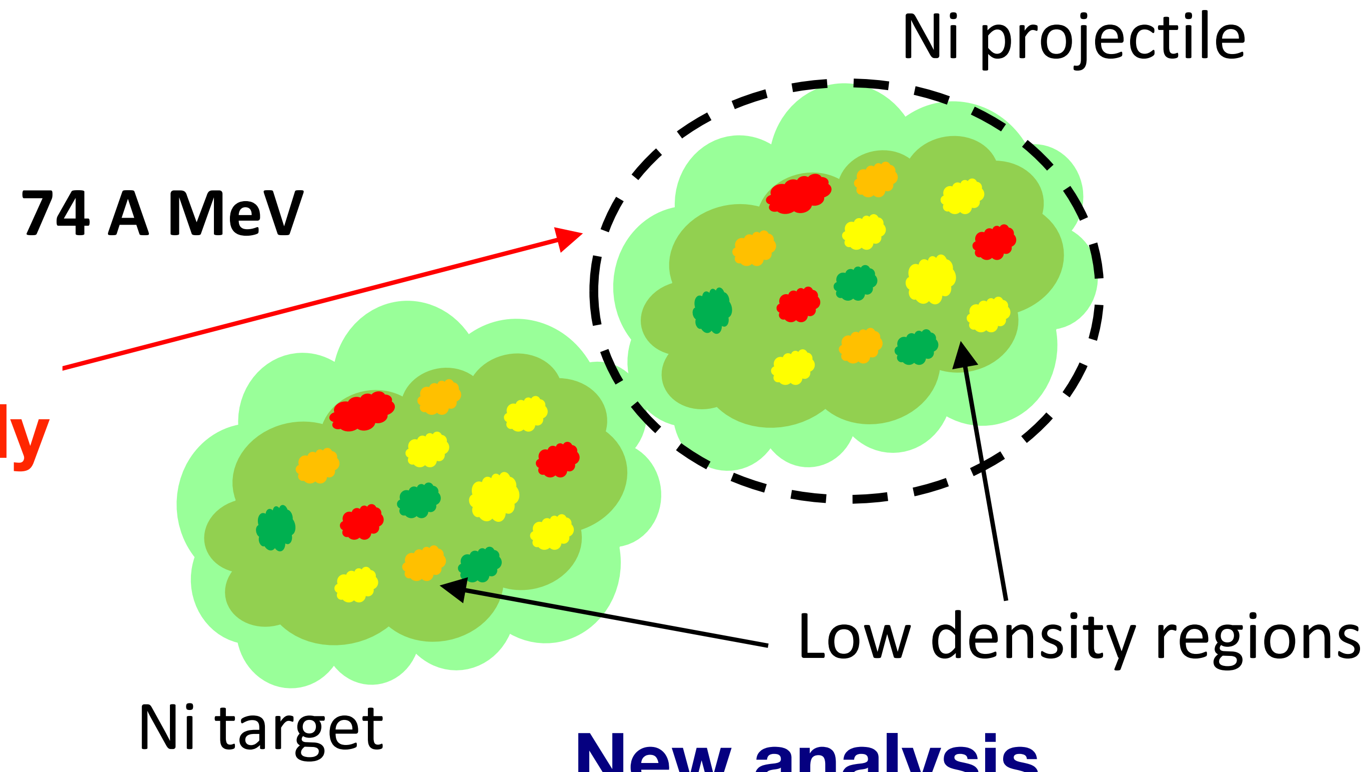
System 136Xe + 124Sn. The equilibrium constants as a function of the density.

$$K_c(A,Z) = \frac{\rho_{AZ}}{\rho_{11}^{Z}\rho_{10}^{A-Z}}$$



Interesting regions to study experimently

Previous analysis
Mid velocity source
→limited cluster diversity



New analysis
Vaporization like source
→nuclear matter state is compatible with a gaseous phase composed only of clusters

FAZIA: other opportunities – R&D for the future detector upgrade

Future

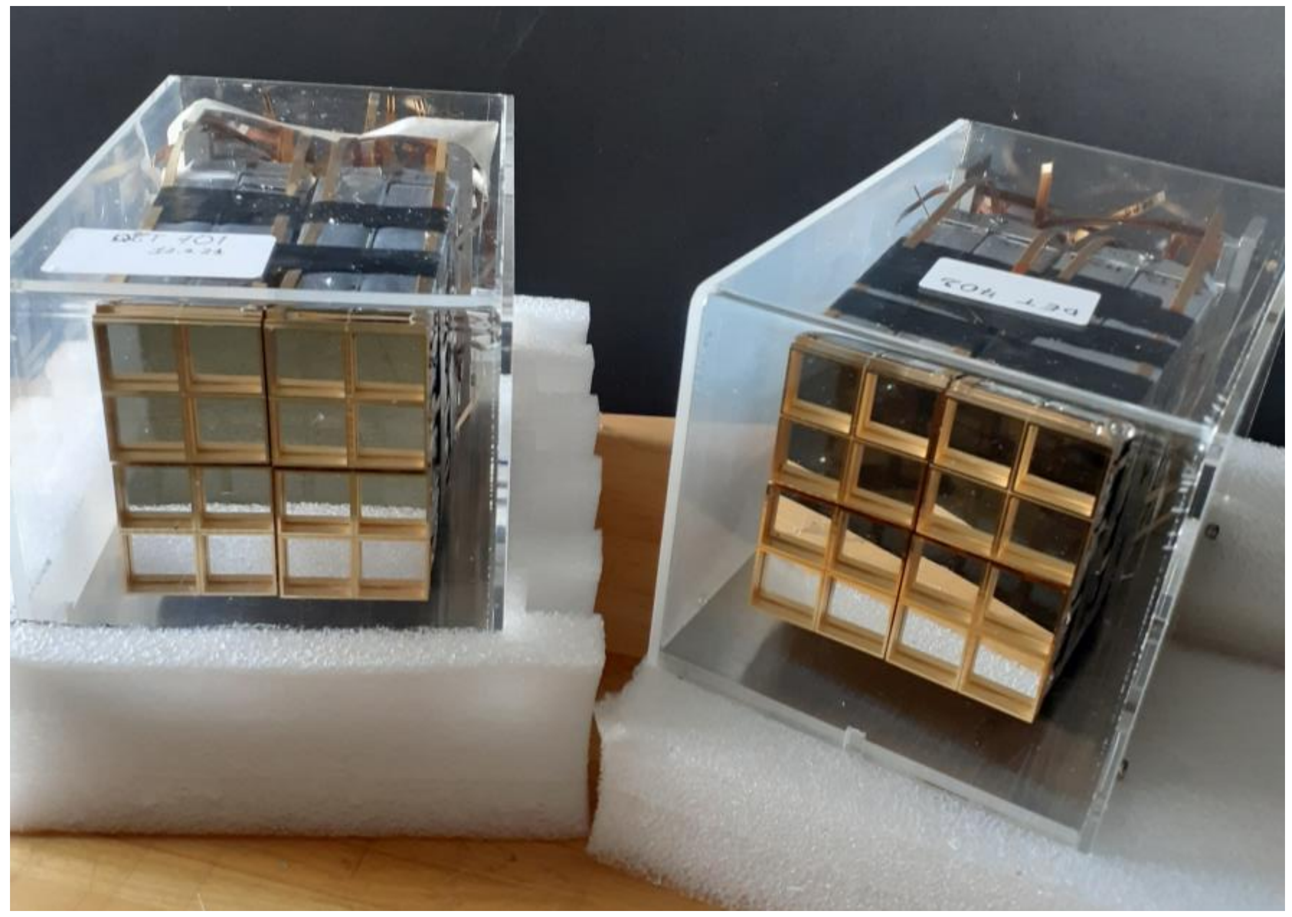
- Extended identification capability, better granularity
- Flexible installation in the limited space (vacuum chamber)
- Application of the modern technology to detectors and FEE
- Larger acceptance: Plan to increase the number of FAZIA blocks in difference places (Europe and Korea) to benefit from any opportunities to perform more comprehensive measurements

Opportunities under R&D

Selective slides mainly showing Korea-side R&D

- **Thicker (750 µm) silicons detectors (Korean initiative)**
    - Interesting for higher energy physics (better A resolution)
    - Probing the high density dependence of symmetry energy of the EoS, thus with heavy ions at high E beam
- **Thinner silicons detectors**
    - For lower energy physics
    - High intensity radioactive beams are in development around the world Spiral 2 (Ganil), SPES (Legnaro), RAON (Korea)... which will start with low energy beams
    - 100 µm chip under investigation in Korea & 30-40 µm chip under discussion with Micron Semicon UK
- **Exploring the possibility of future production of FEE boards in Korea**

Silicon sensor development

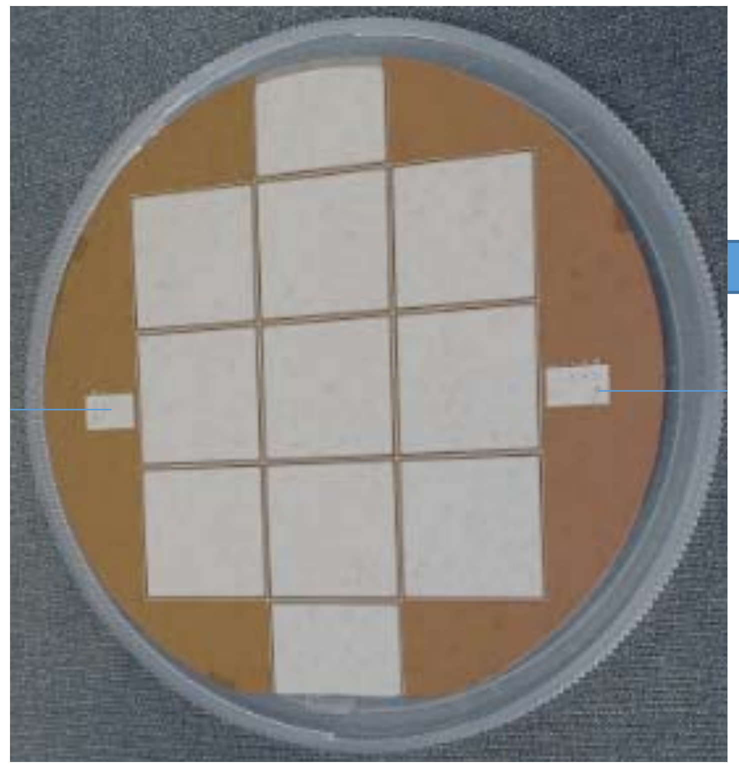


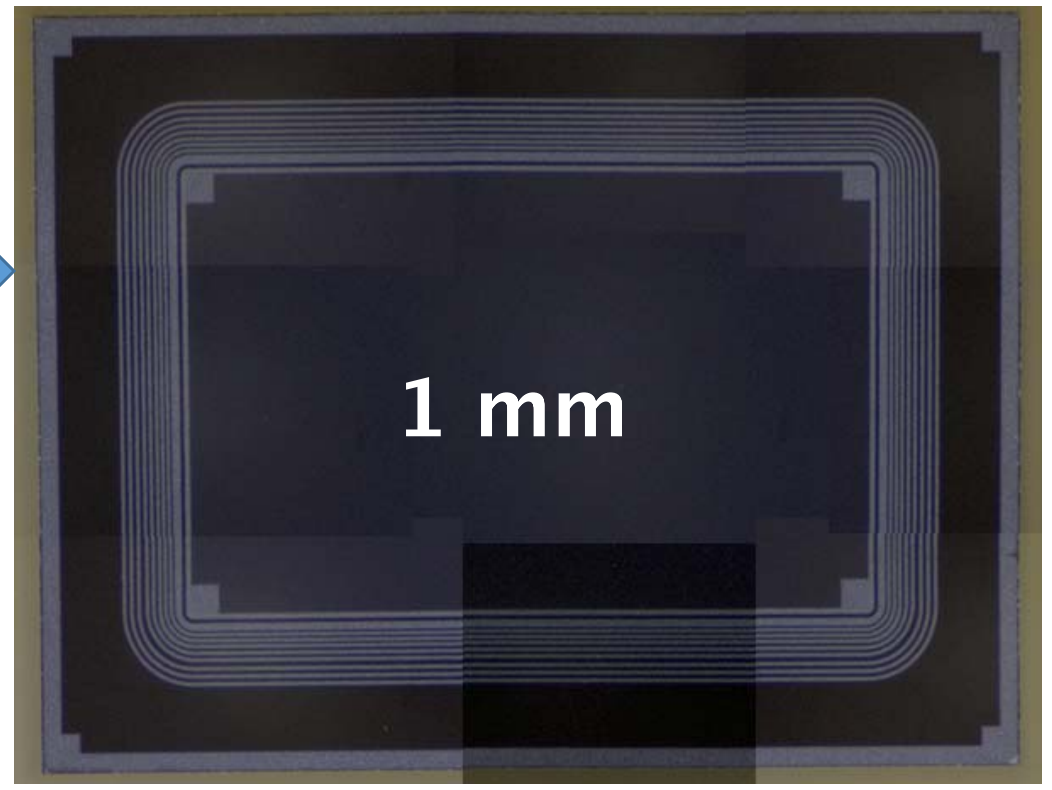
- 750 μm thickness chip
  - wafer investigation: 750 μm wafer was supplied from Korea
  - chip processing was done in Germany and tested by FAZIA team

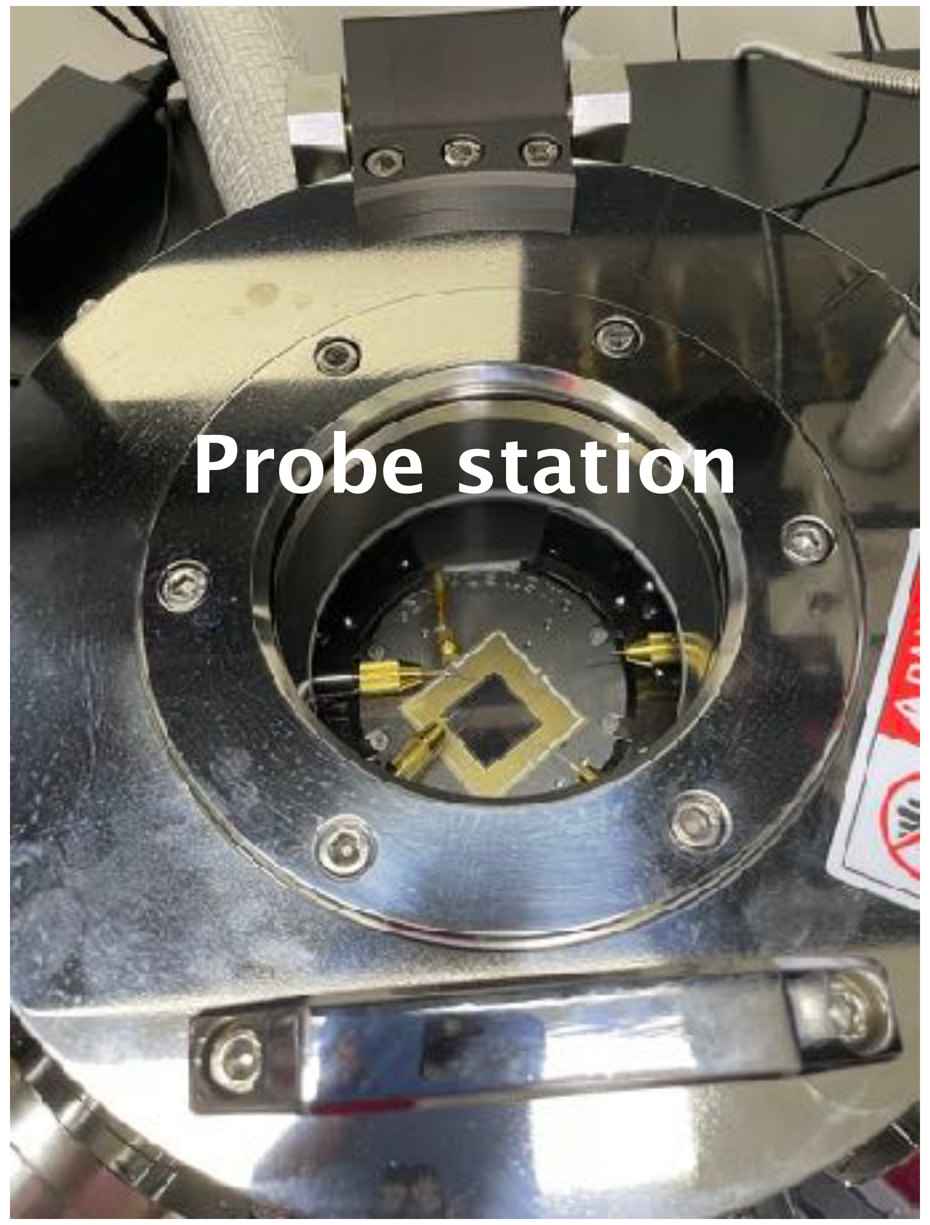
quartetto	batch	wafer	pad	rev curr. @340V CIS	internal reference (neglect)	date of test	bias voltage	rev current Florence	geometry Reverse o Direct	pulser width (ch)	241Am peak pos (ch)	241Am peak width (ch)	Resolution %
7501	401778	7	6	13,5	III	7-1-2021	300	12	r	8.2	3131,7	16,2	5,17E-01
7501	401778	7	8	0	II	7-1-2021	300	10	r	7.7	3135,4	13	4,15E-01
7501	401778	7	5	10,5	IV	7-1-2021	300	10	r	8.6	3135,9	13,1	4,18E-01
7501	401778	7	5	10,5	IV	7-1-2021	330	11	r	8.6	3140,2	13,3	4,24E-01
7501	401778	7	7	13,4	I	7-1-2021	300	2000	r	0	0	0	-

  - Assembled by the Italian (INFN @ Florence) group & included for the beam test during E818 Exp.

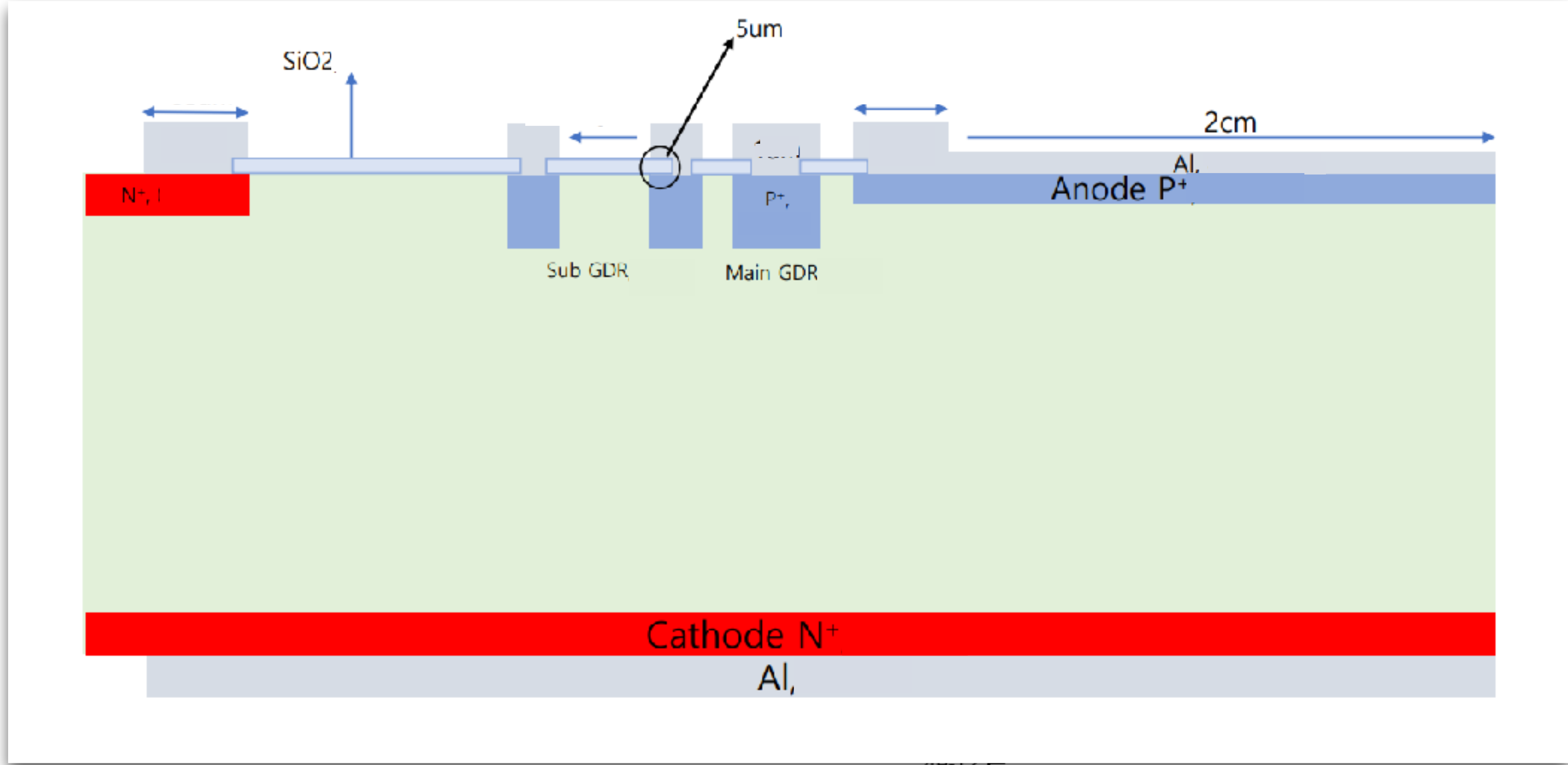
- 1 mm thickness chip
  - produced & tested in Korea → doesn't satisfy the goal
- 150 μm thickness chip
  - produced & tested in Korea → doesn't satisfy the goal
- Restarted from the design to produce thicker chip



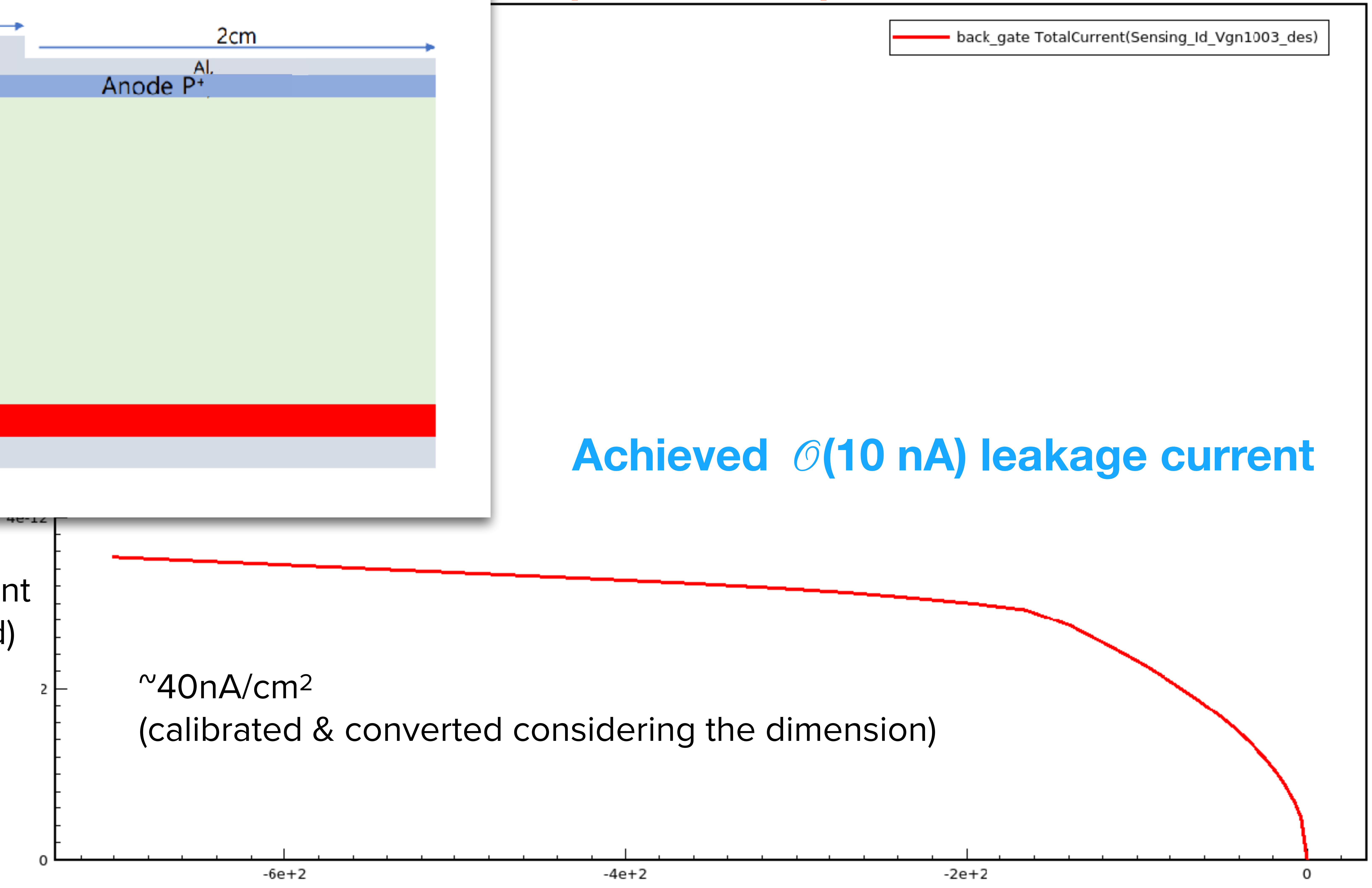




Leakage current simulation based on the final design



To produce 750 μm thickness sensor in Korea



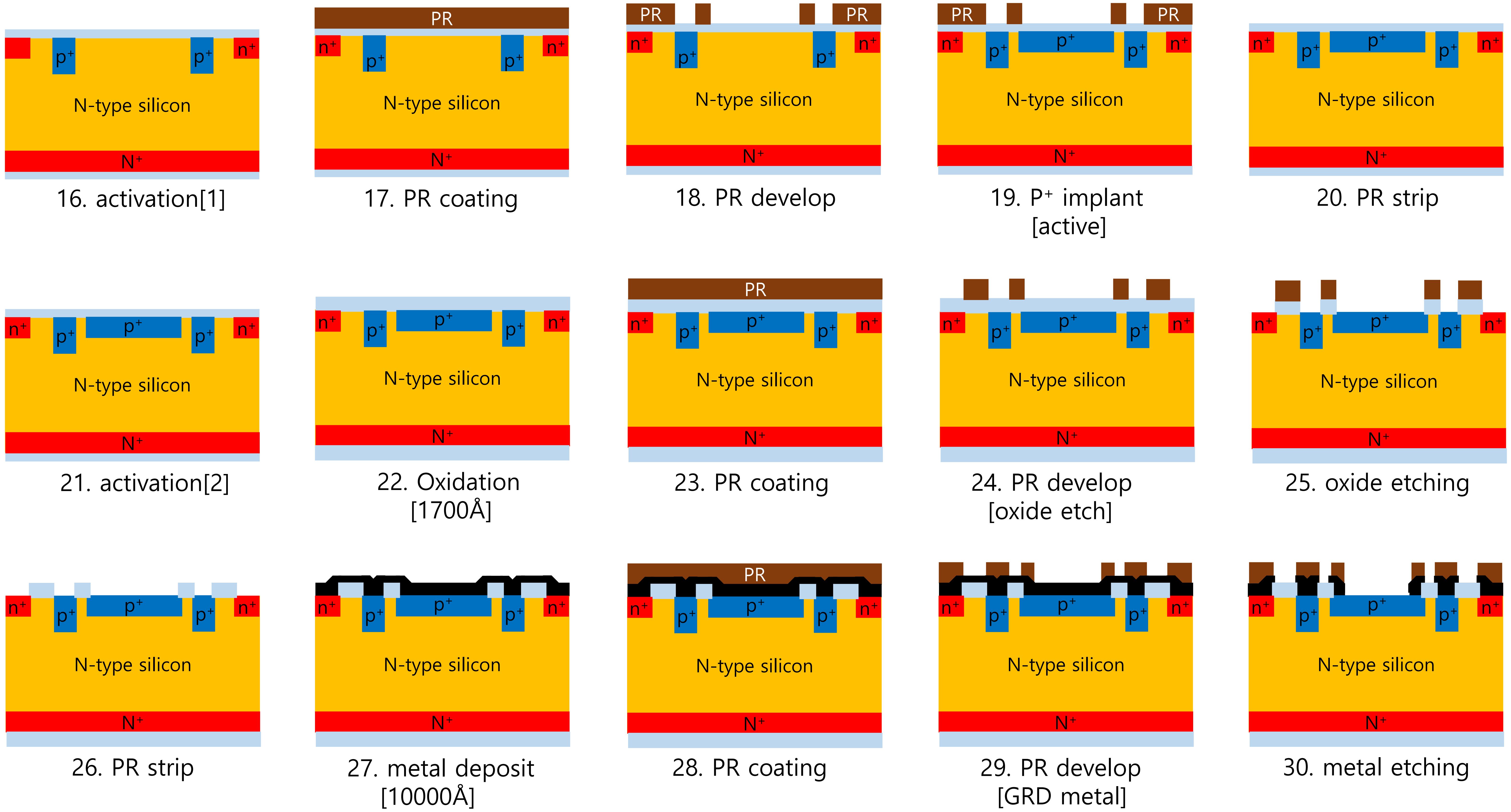
Achieved $\mathcal{O}$(10 nA) leakage current

~40nA/cm²
(calibrated & converted considering the dimension)

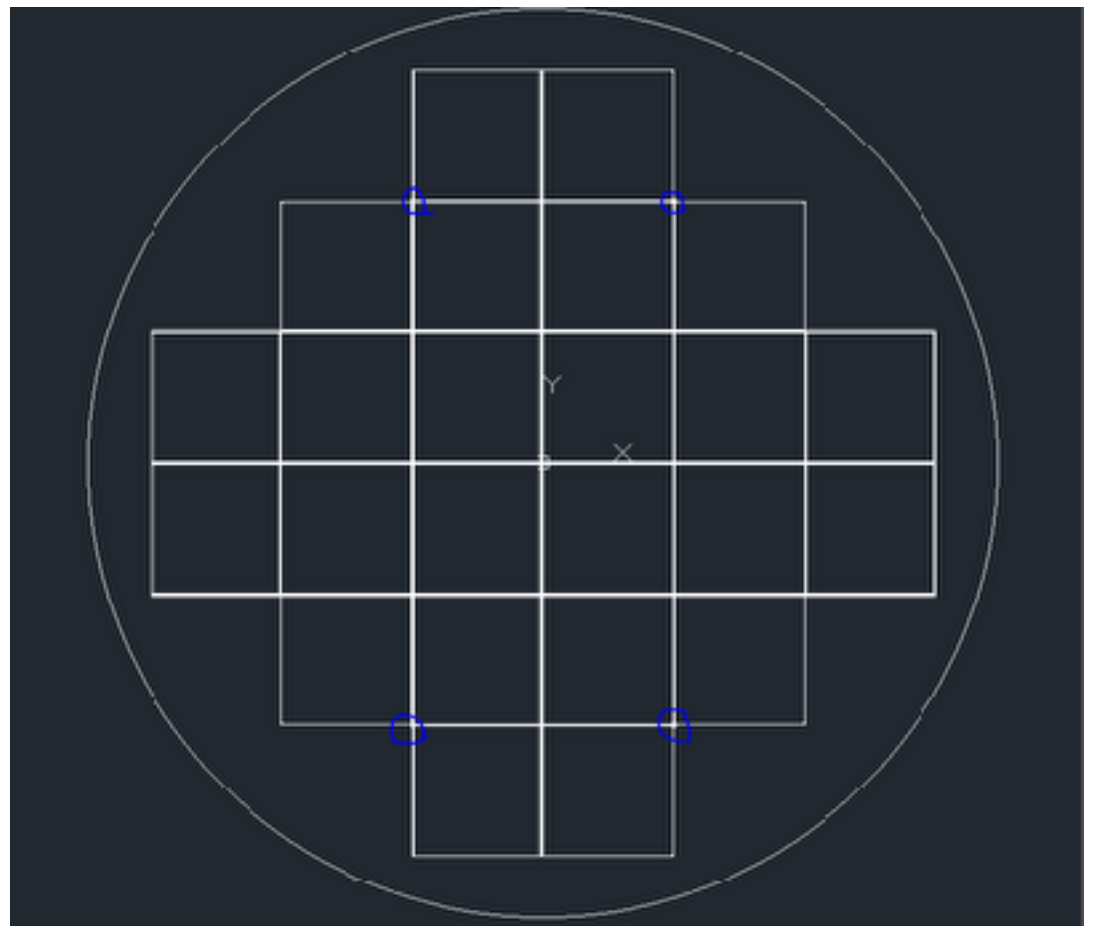
Sensor design was finalized based on it

Sensor fabrication

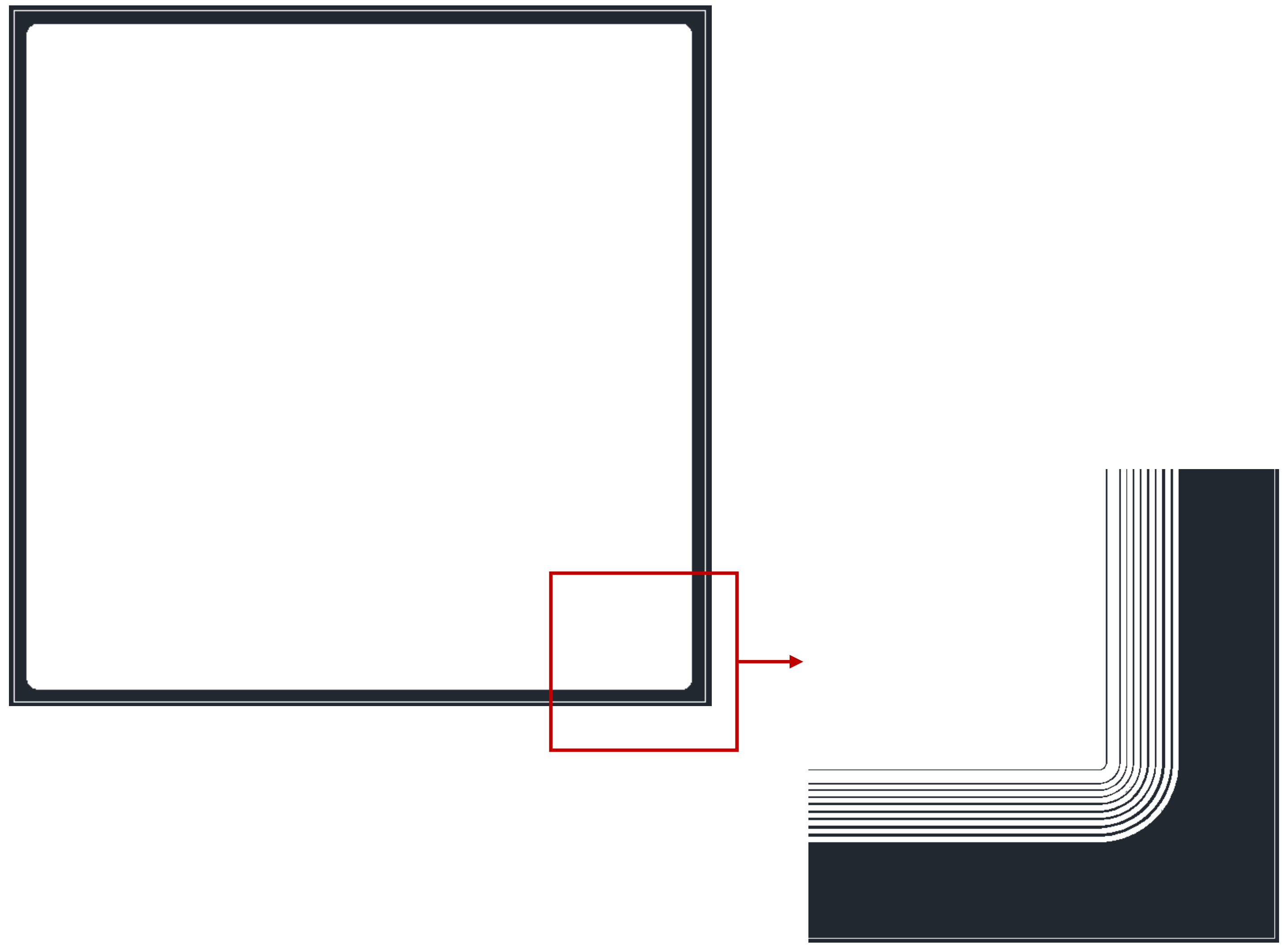
Flow charts prepared



Mask designed



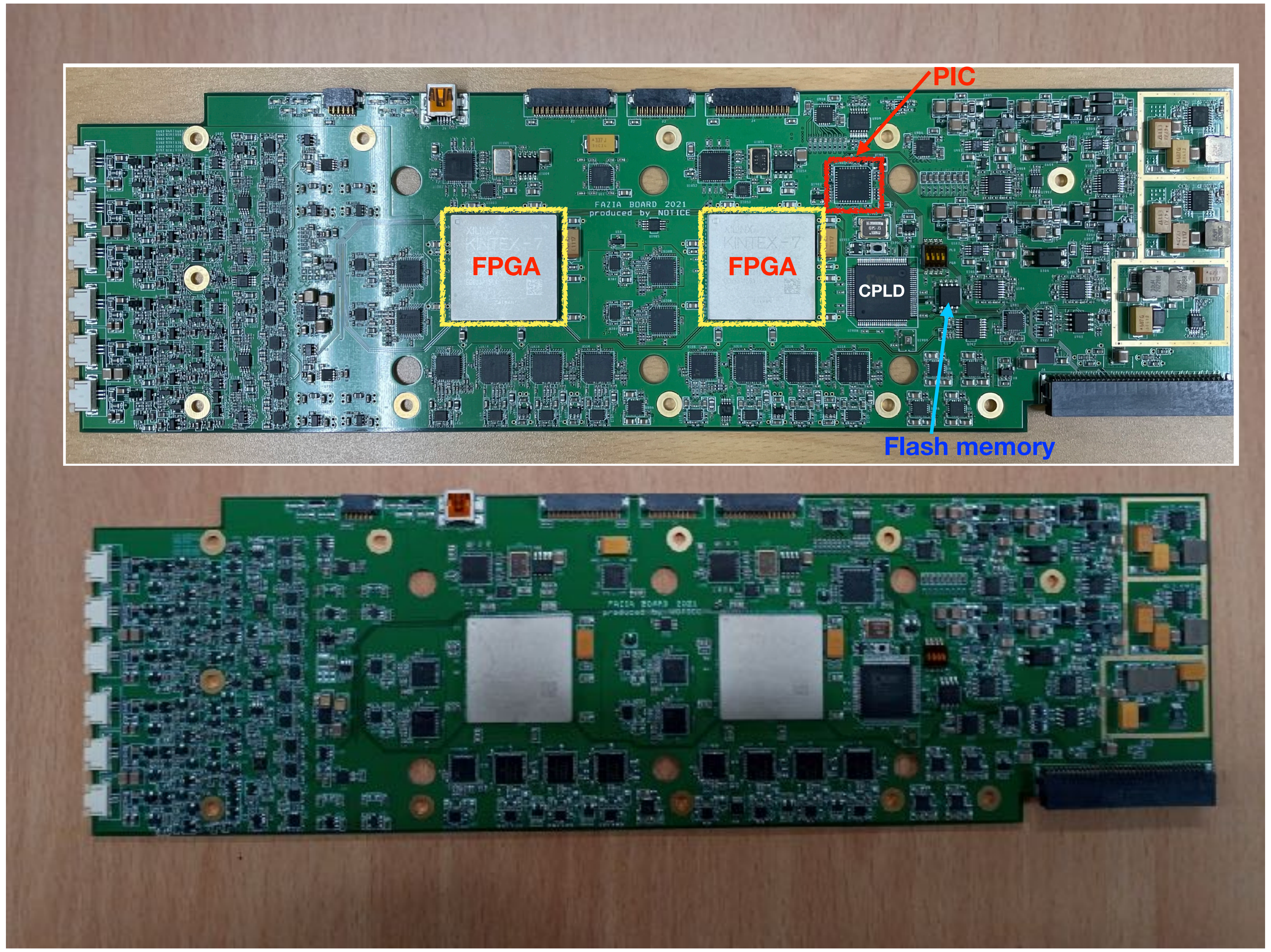
#3 active



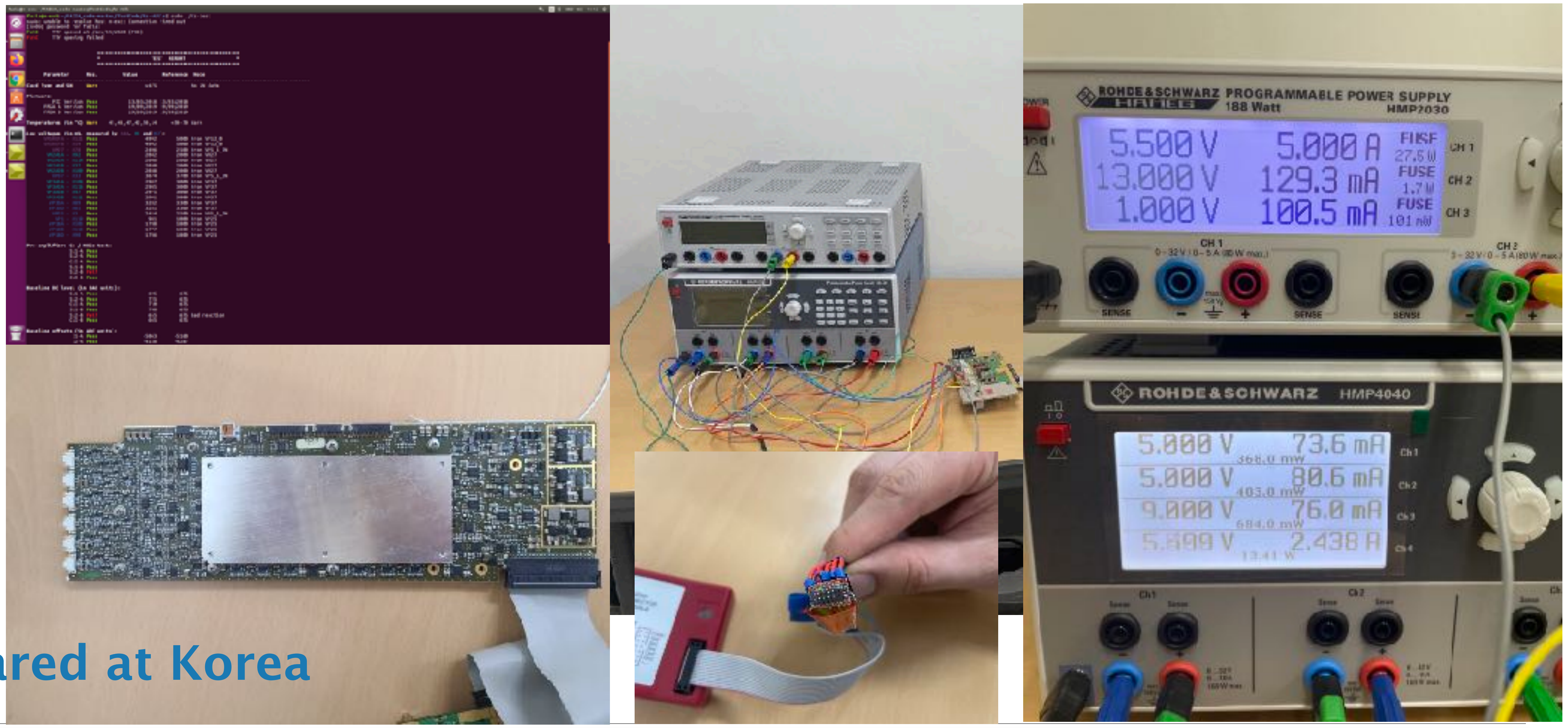
Run sheet for the fabrication was finalized → submitted this week!
(ETRI & National Nanofab Center (NNFC) for the future in Korea)

The production is to be done by the end of this year.

FEE development & production

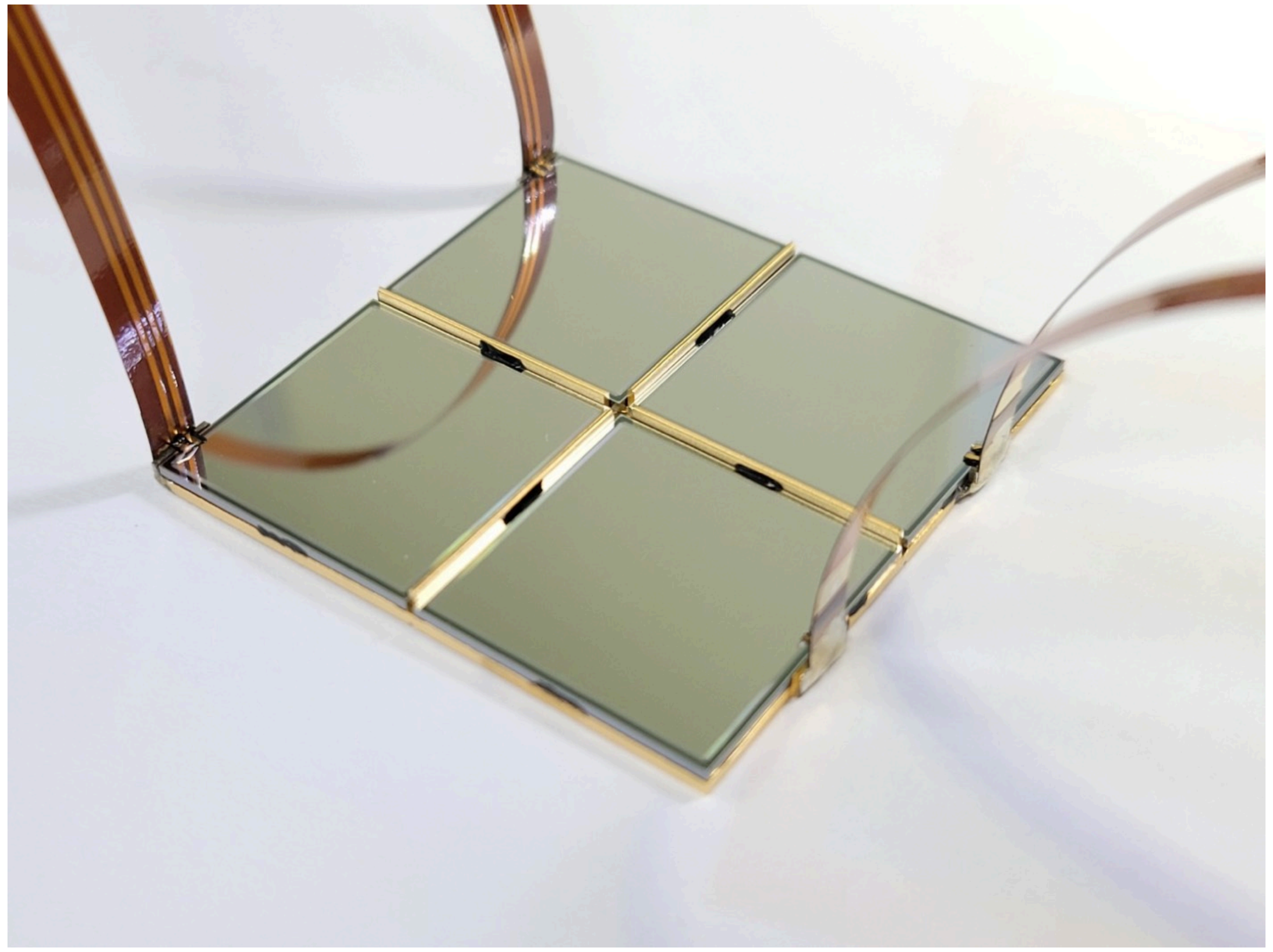


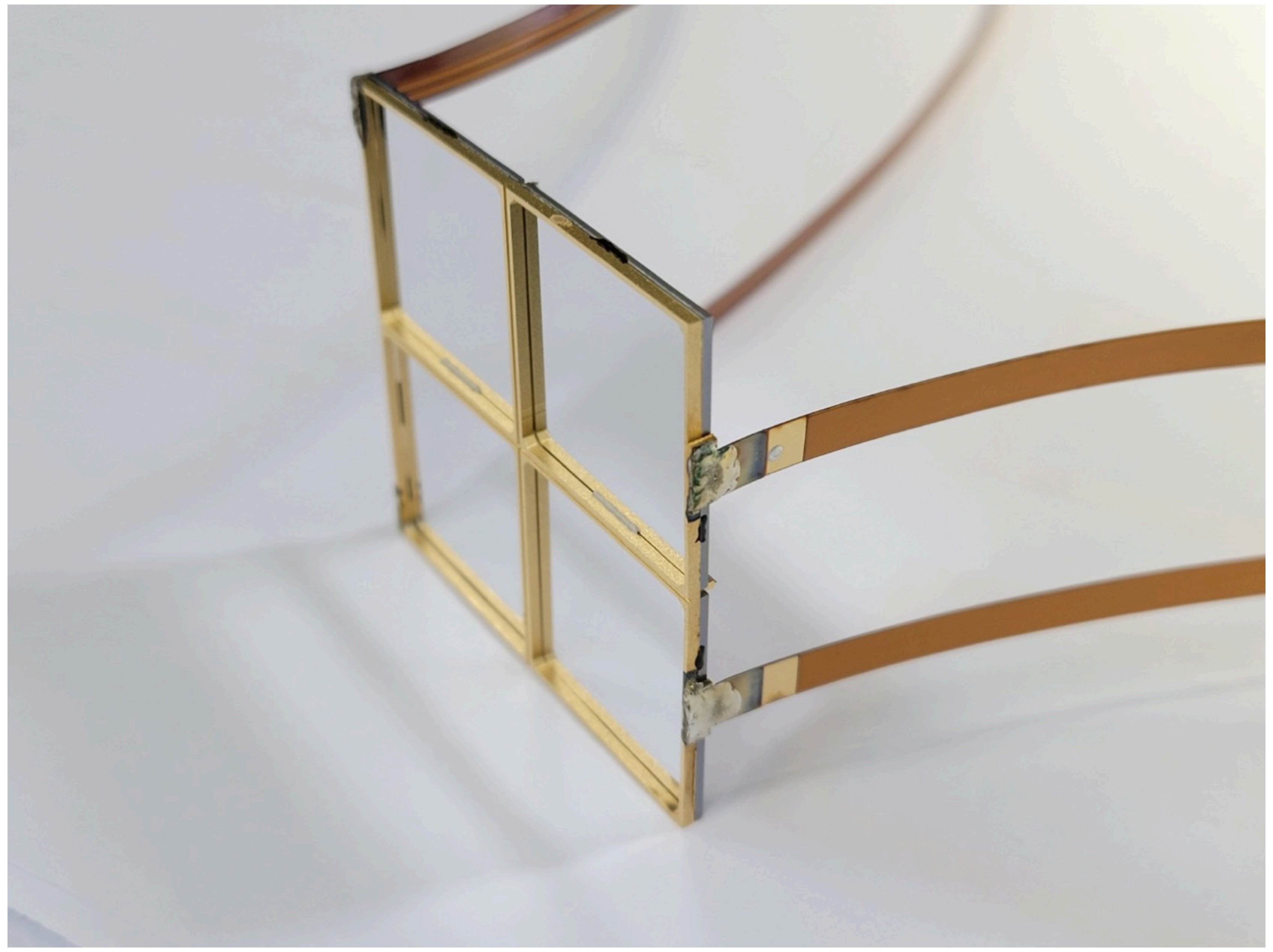
- Two prototype boards were produced by the company NOTICE
  - Design from the current FAZIA
  - Out-of-date digital parts → replaced
  - New FPGA chips → new VHDL software developed
- Tested at GANIL; no major issue, under further commissioning
- Discussion ongoing for the next version of the board with 'one FPGA chip', 'reduced board size', & 'separation of the preamp stage from the rest of the digitizers' (together with NOTICE)

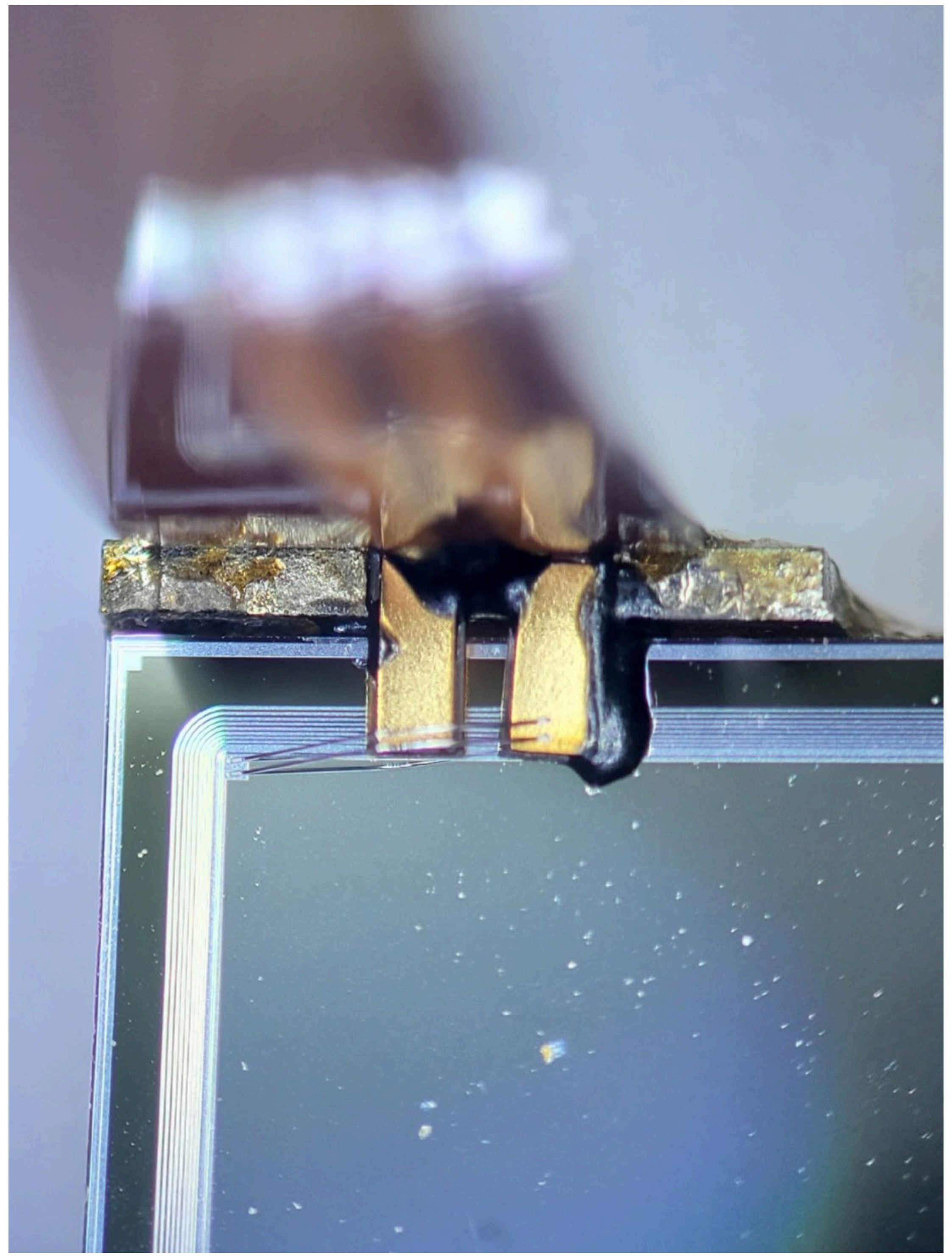


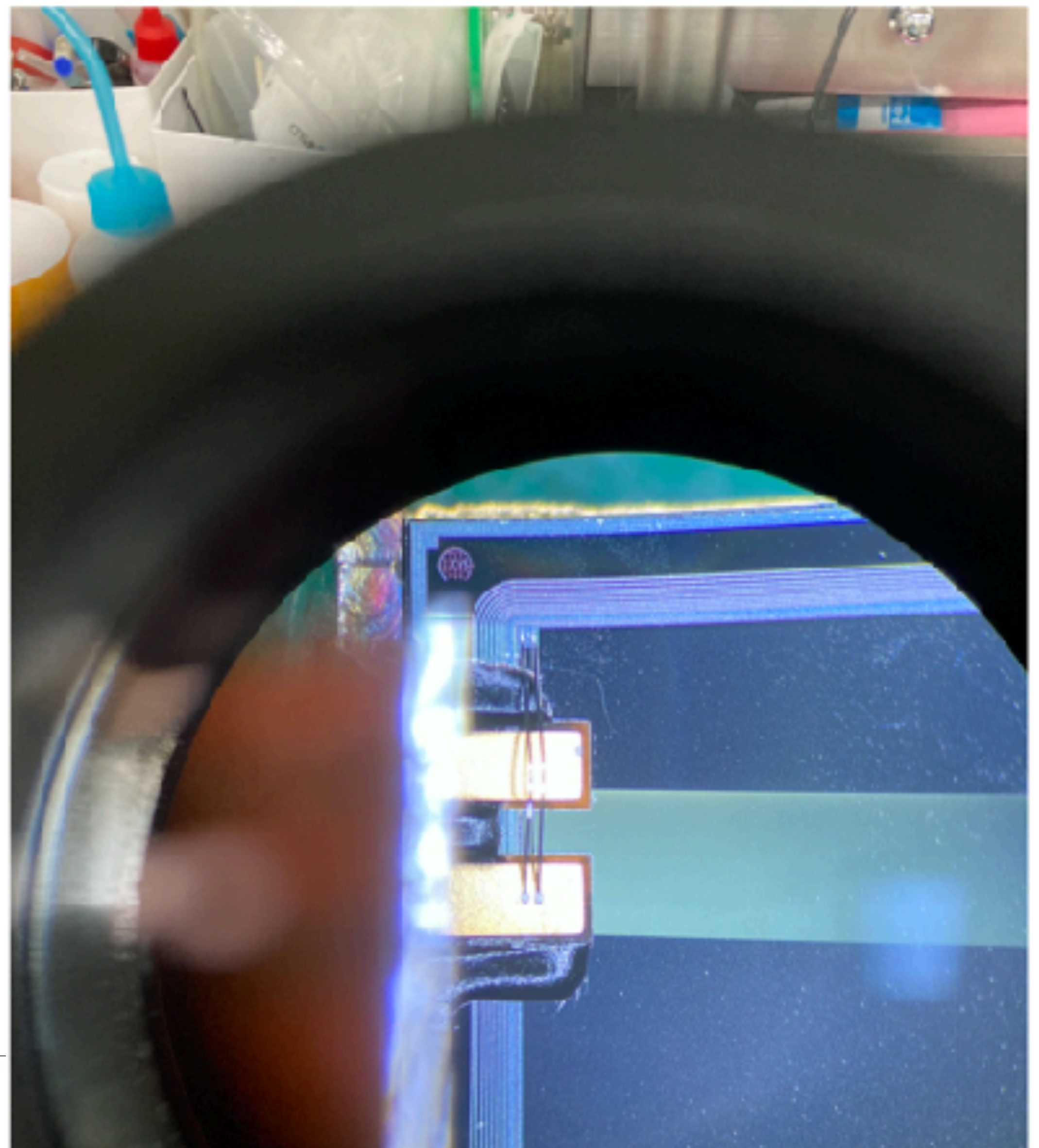
Test setup prepared at Korea

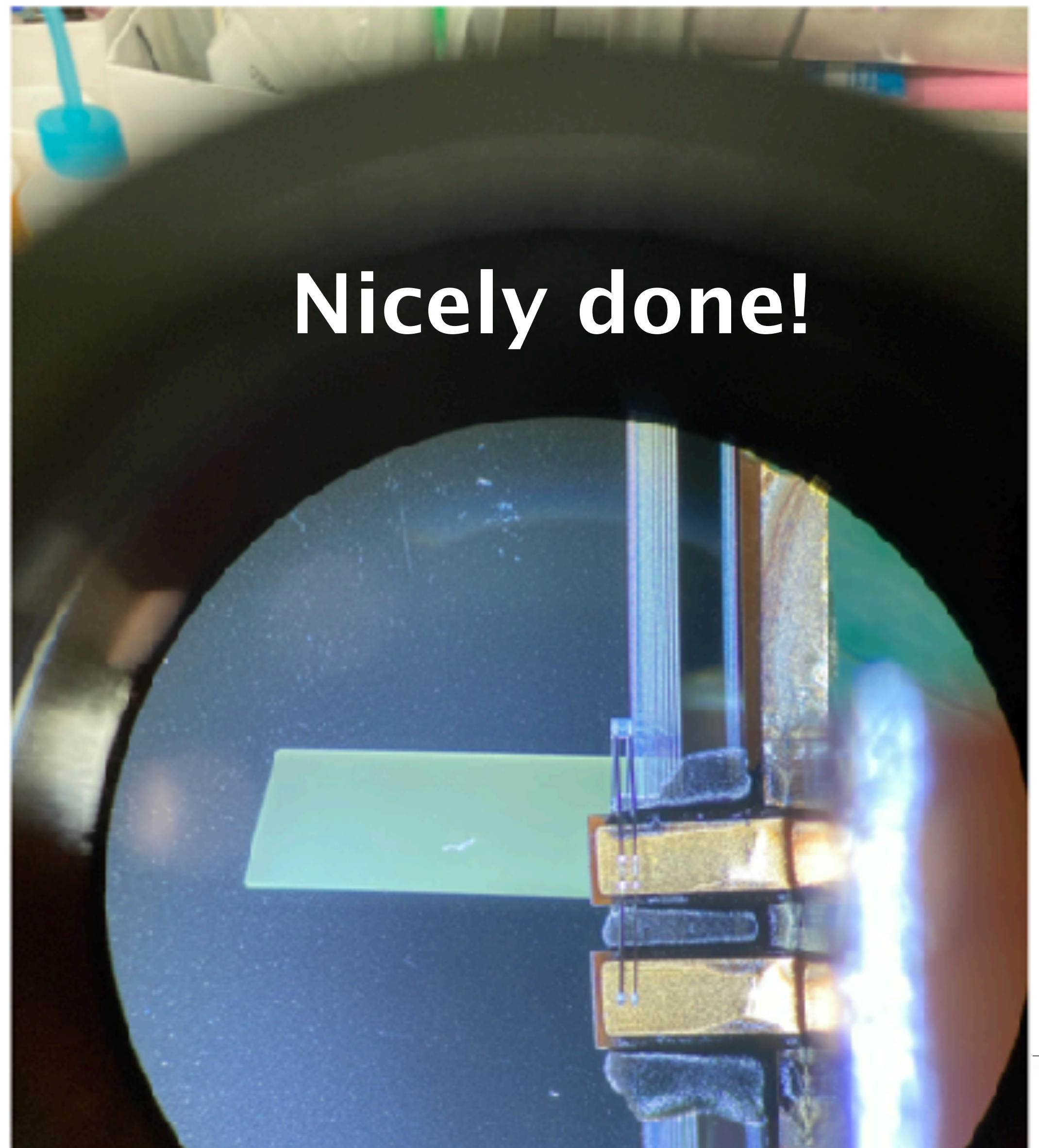
Quartetto production in Korea

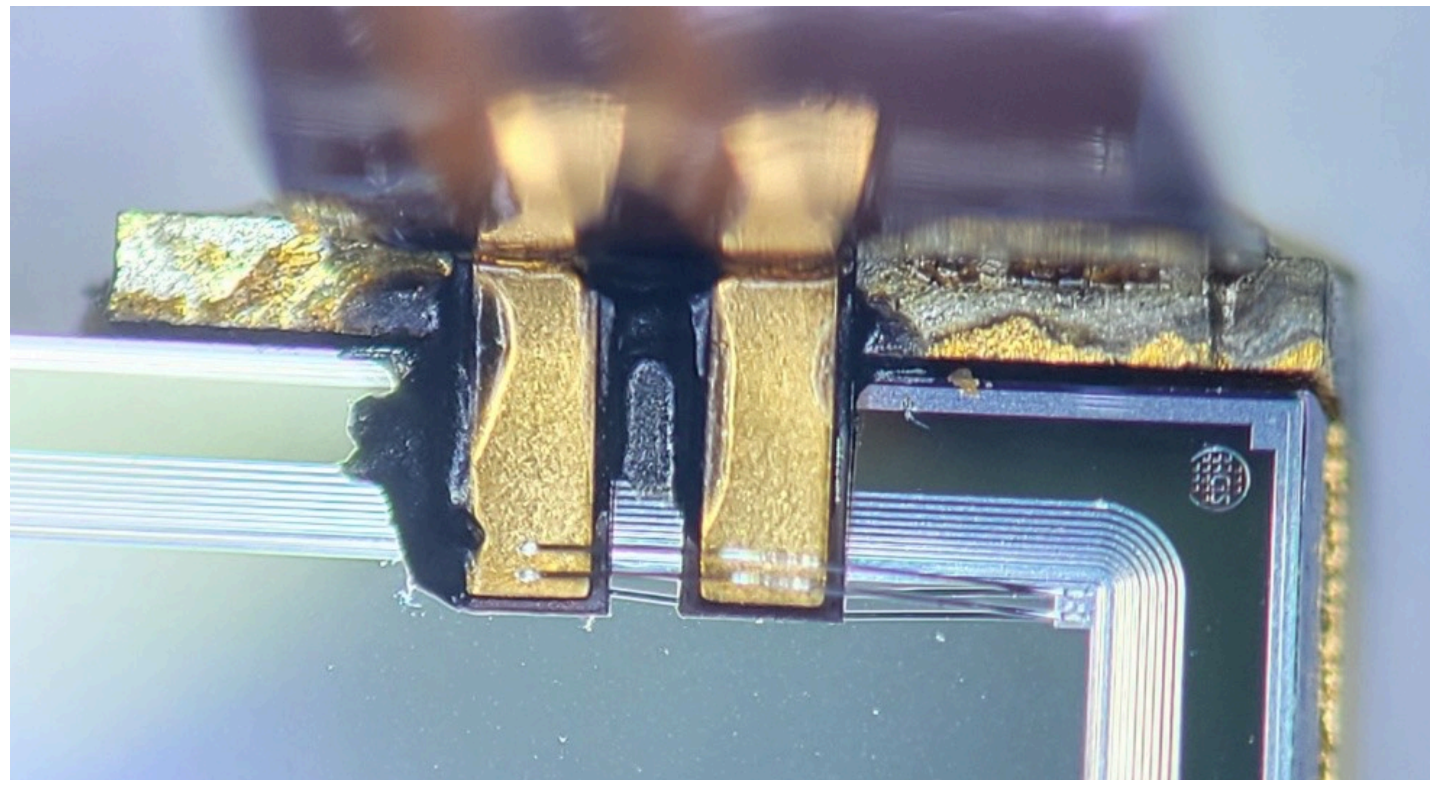












Chip mounting & wire-bonding by the company MEMSPACK
Quartetto frame from FRANCE

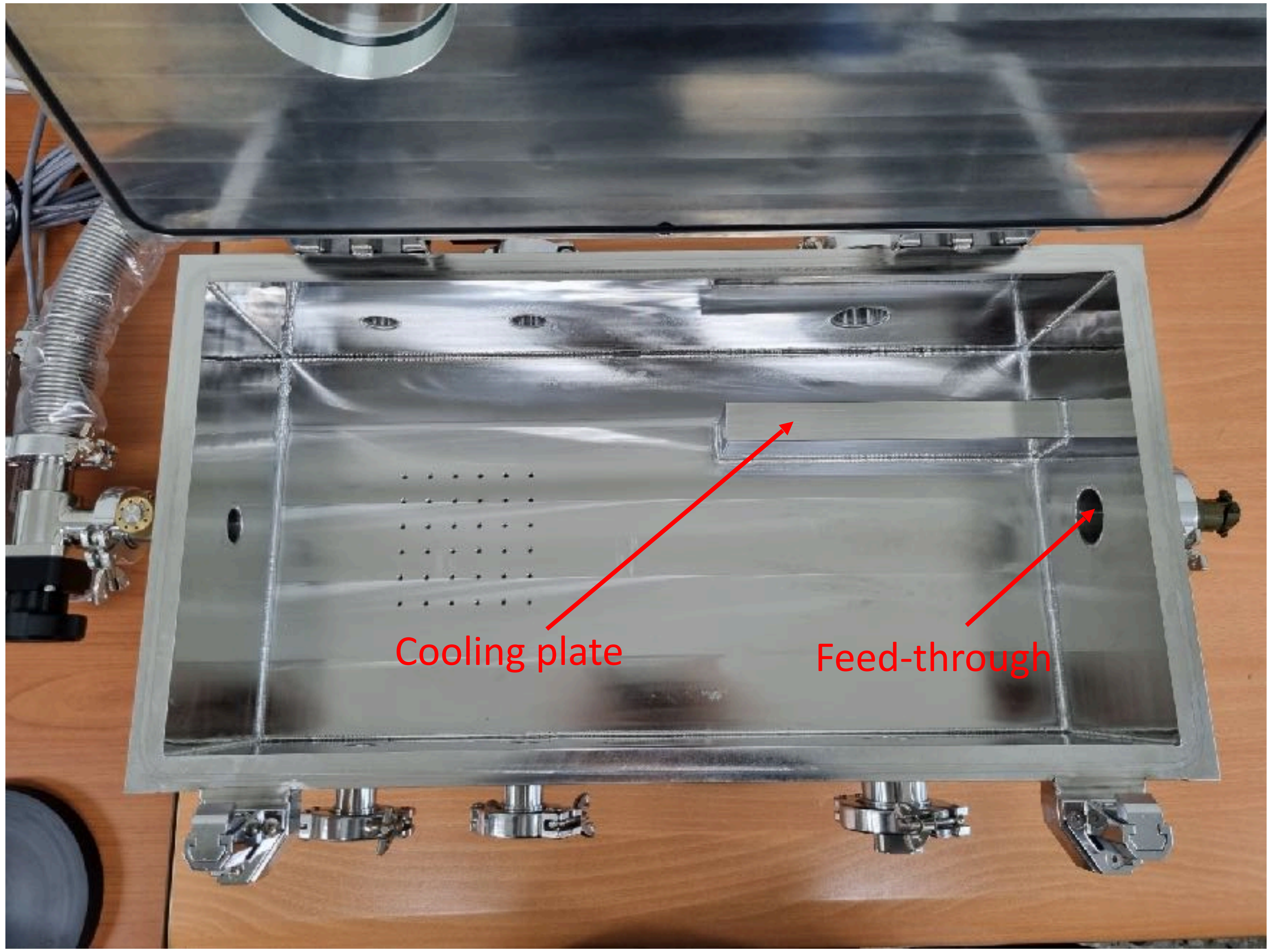
Source test setup in Korea

Constructing lab. test system for Silicon sensor characterization

Cooling machine

Vacuum chamber

Vacuum pump



Vacuum chamber interior

Special boards with preAmp ONLY were produced for the source test.

Summary and outlook

- **FAZIA has a good isotopic resolution for charged particles produced in heavy ion collisions at intermediate energy (from 15 to 100 A MeV): up to Z(A) ~ 54 (25)**

- **FAZIA was coupled with INDRA for the 2019 & 2022 campaigns with the successful data taking**

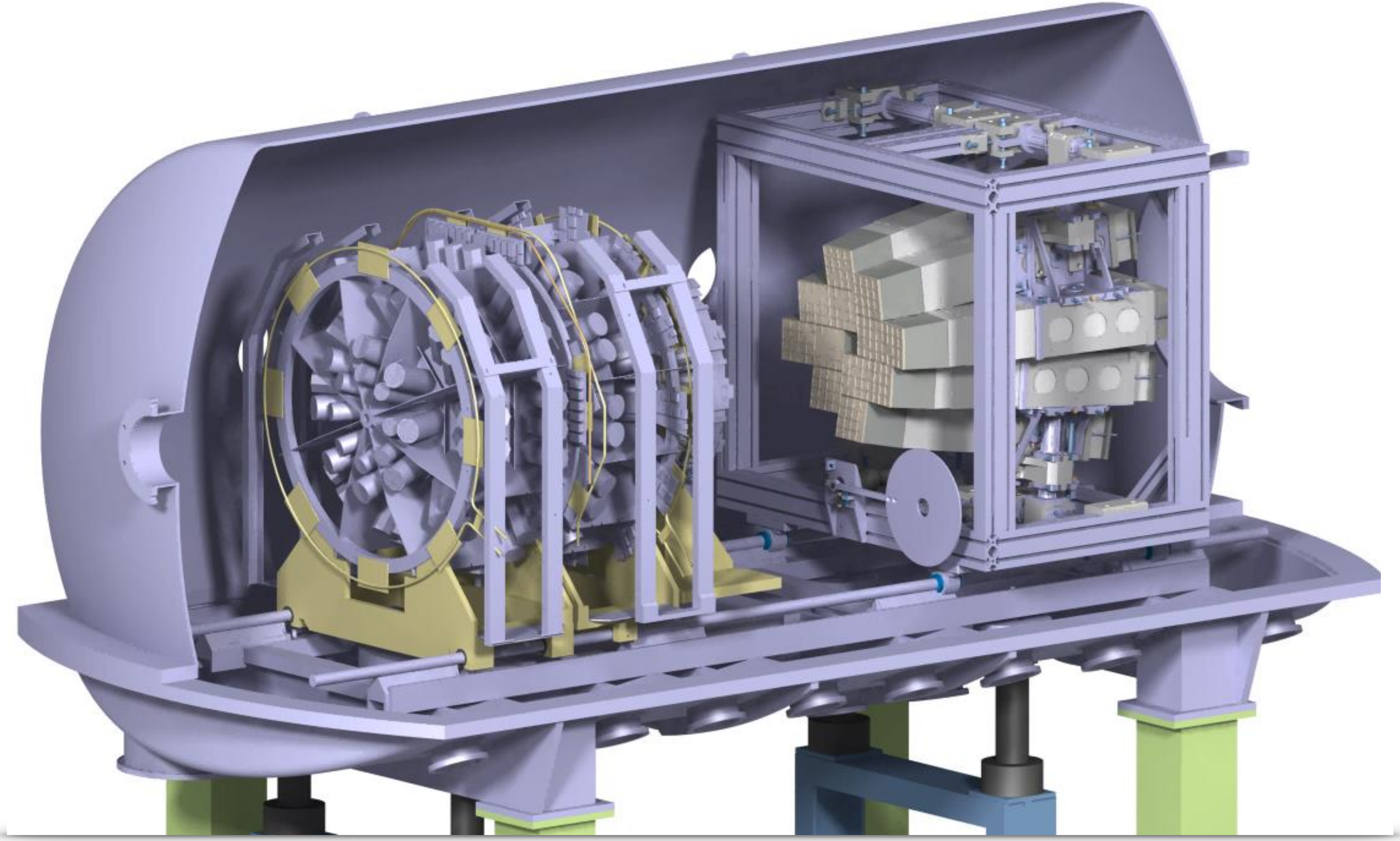
- **The results of commissioning and physics campaigns are providing constraints on the symmetry E of the EoS of nuclear matter for both microscopic and macroscopic physics (from nuclei to the stars).**

- **In the future, the goal is to improve its capability and increase the number of FAZIA blocks available in different places to benefit from any opportunities to perform excellent measurements → R&D is ongoing!**

Thank you for your attention!

Extra Slides

The FAZIA-INDRA in vacuum chamber



FAZIA commissioning phase: stable ^{40}Ar, ^{84}Kr beams

FAZIA commissioning phase at LNS Catania 2013-2018

FAZIA May 2013
1 block + telescopini
84Kr at 35A MeV

FAZIA December 2014
2 blocks horizontal plane 10 UTs
^{84}Kr + ^{58}Ni, ^{93}Nb & $^{112-124}$Sn at 24.75 A MeV

ISOFAZIA June 2015
4 blocks horizontal plane 25 UTs
^{40}Ar at 35 A MeV & ^{80}Kr + $^{40-48}$Ca at 35 A MeV

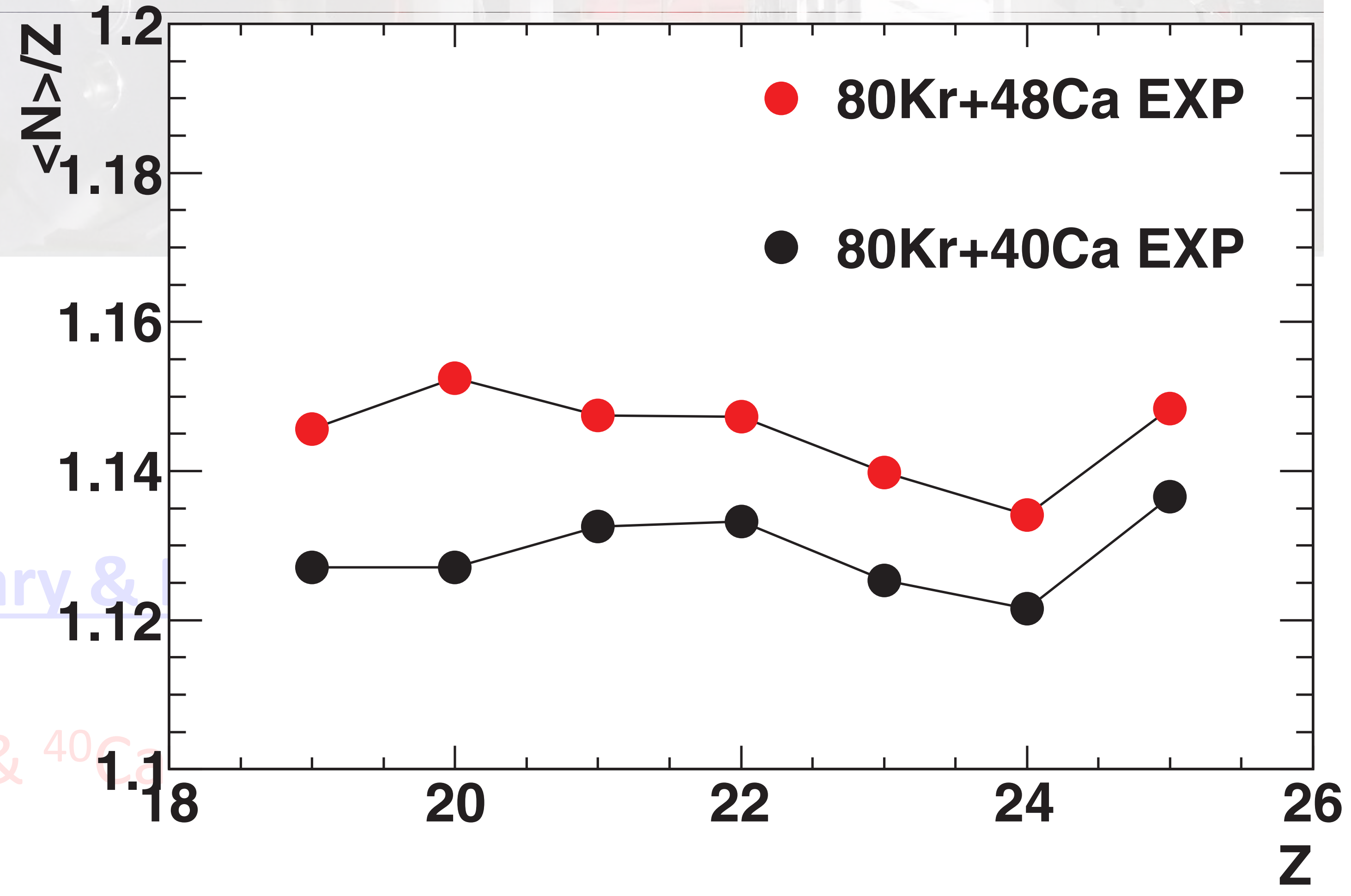
FAZIASYM December 2015
4 blocks wall configuration
$^{40-48}$Ca + $^{40-48}$Ca at 35 A MeV

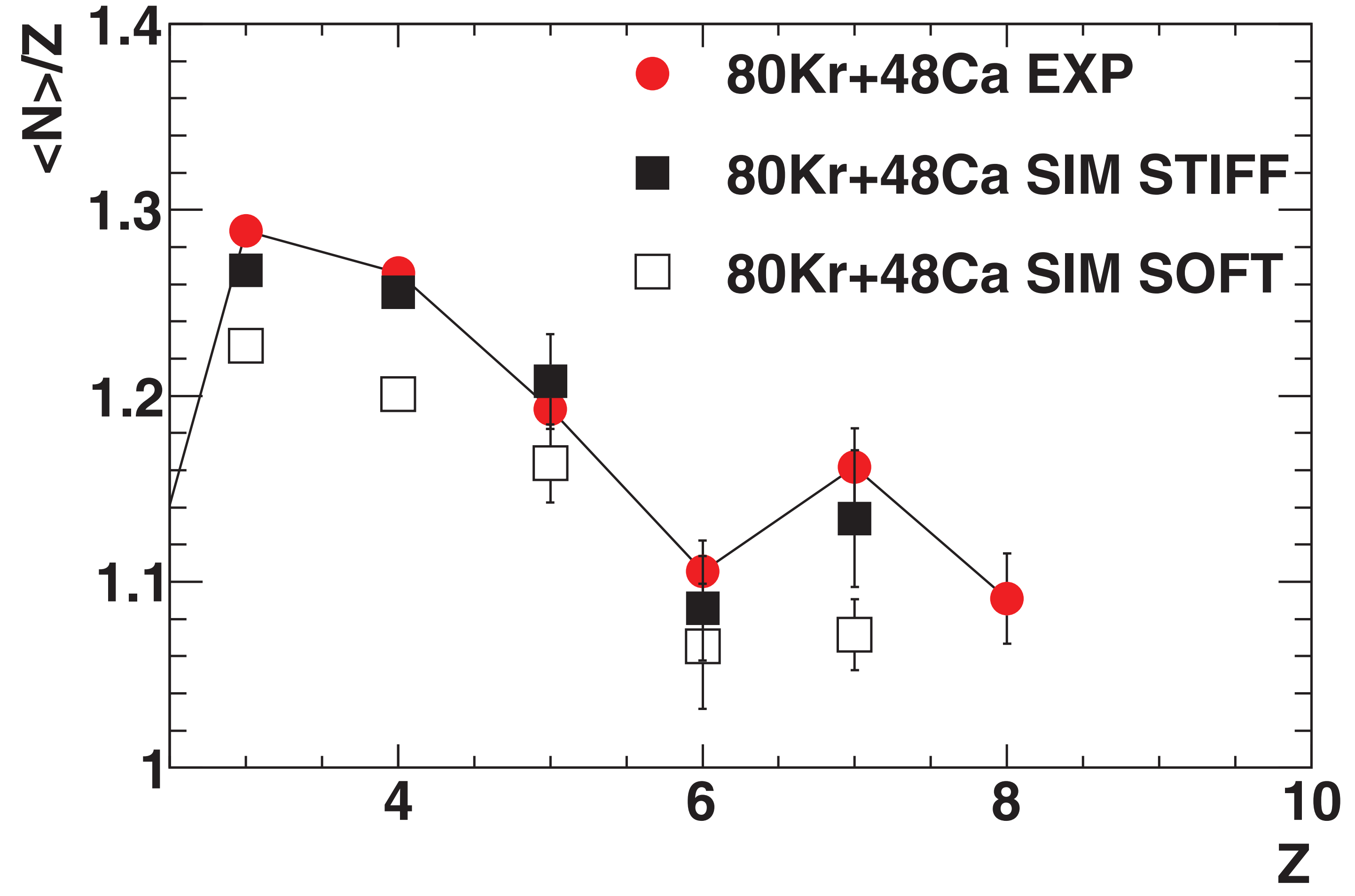
FAZIACOR March 2017
4 blocks wall configuration
^{20}Ne & ^{32}S + ^{12}C at 25 & 50 A MeV

FAZIAPRE test October 2017 experiments in February & ...
4 blocks wall configuration, plus 2 lateral blocks
$^{40-48}$Ca + ^{12}C at 25 & 40 A MeV + few runs with ^{27}Al & ^{40}C...

FAZIAZERO July 2018
4 blocks wall configuration, plus 1 lateral bloc & one at 0°
^{12}C + ^{12}C & (CH_2)n at 62 & 80 A MeV

ISOFAZIA was the first physics experiment performed by the FAZIA Collaboration after the R&D phase [1]. A ^{80}Kr beam ($N/Z = 1.22$) at 35 MeV/nucleon, delivered by the superconducting cyclotron CS of INFN-LNS (Catania, Italy), and two different targets, a neutron-rich ^{48}Ca ($N/Z = 1.40$) and a neutron-poor ^{40}Ca ($N/Z = 1.00$) were used, in such a way that the N/Z of the projectile was intermediate between those of both targets. The experimental setup consisted of 4 complete blocks, each one including 16 silicon (thickness: 300 μm) - silicon (thickness: 500 μm) - CsI (thickness: 10 cm, read out by a photodiode) telescopes, located in a belt configuration, covering the polar angles in the range 2.3°–16.6° and symmetrically located with respect to the beam axis.

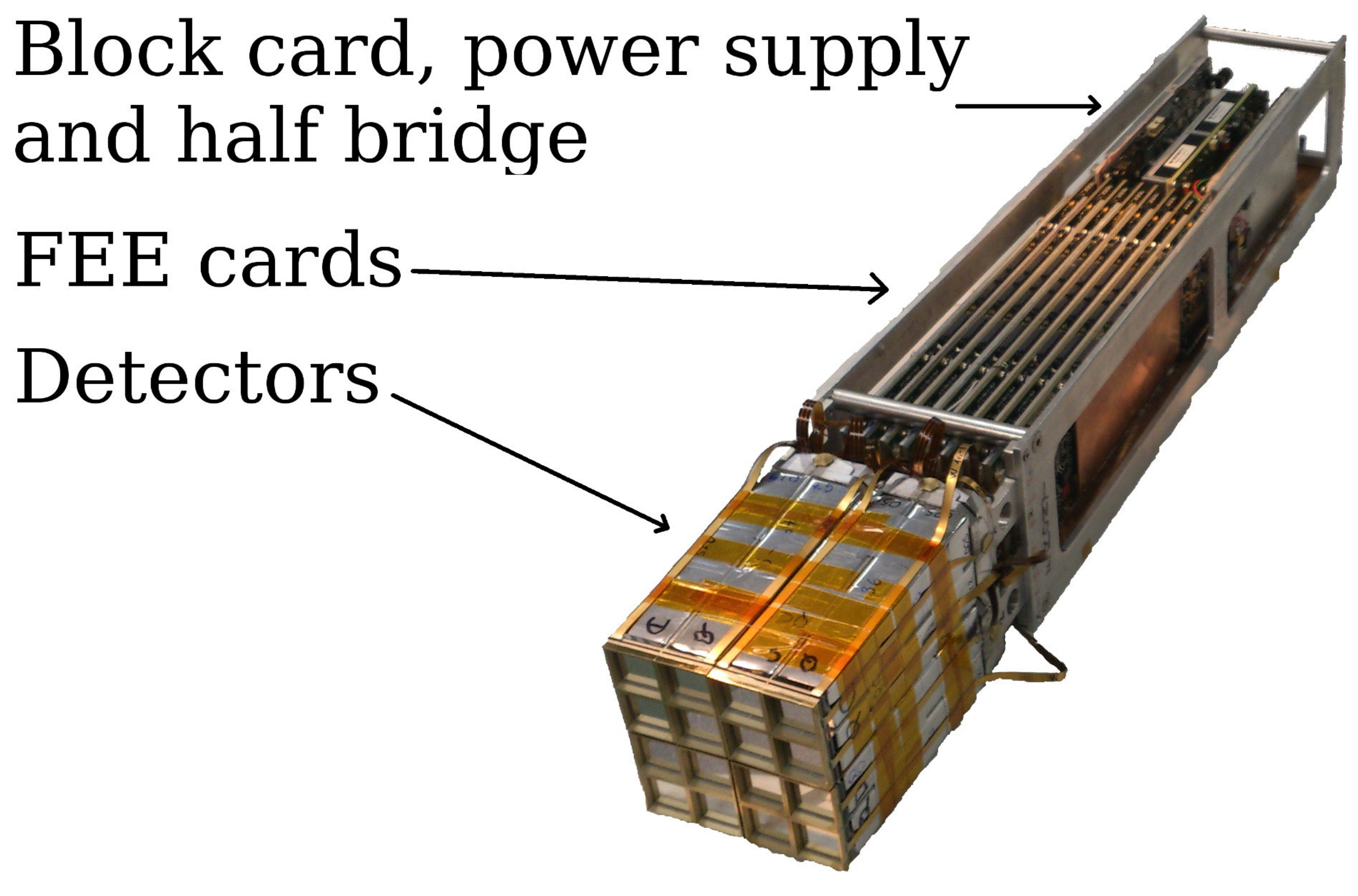




The FAZIA-type detector development for RAON

- Joined FAZIA detector upgrade project in 2019
  - Development of 750 μm thickness chips
  - New FEE board R&D and prototype production including test

- R&D for RAON: targeting producing one FAZIA-type block
  - Development of 1 mm & 150 μm thickness chips
  - New FEE board R&D
  - Production of supporting structures with the help of FAZIA team



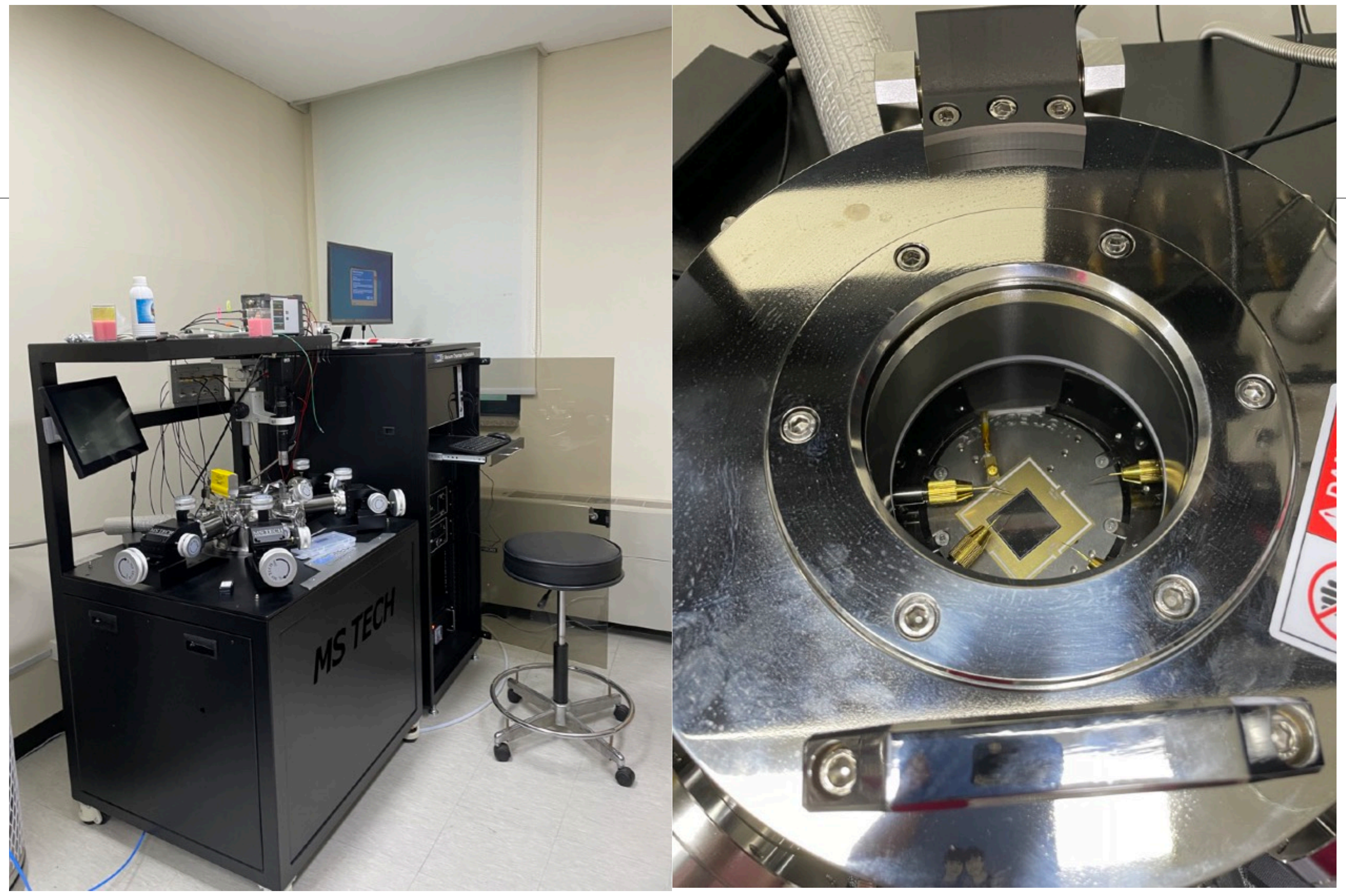
1^{st} visit in May/2019

- Several Korean researchers from Ewha, Inha and Korea university visited FAZIA experiment (during beam time). at the end of May, and discussed where we can contribute as (potential) new collaborators

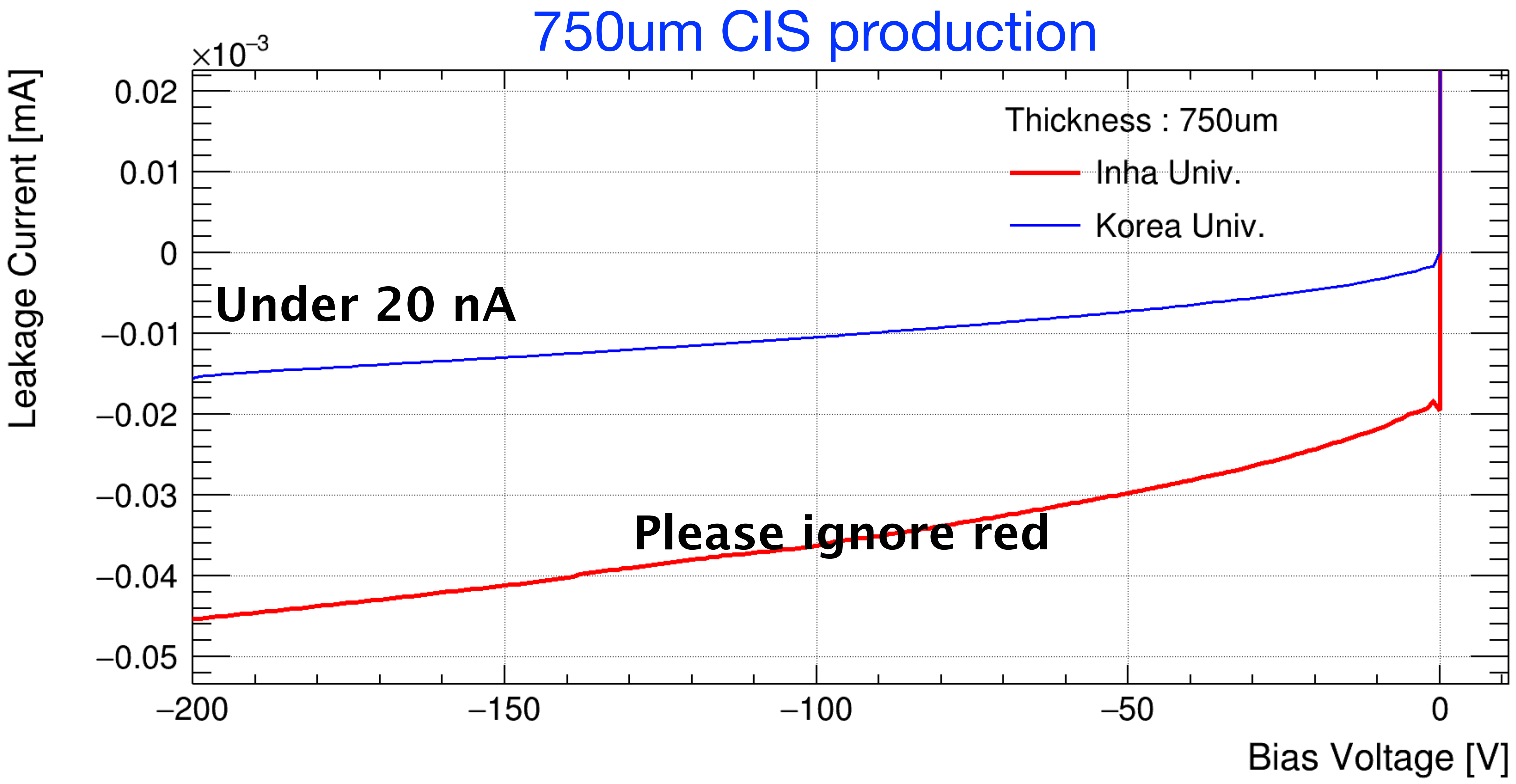
- Korean group starts to investigate
  - if there is a factory in Korea providing thin & ultra high purity Si sensors
  - if there is a company in Korea to produce the electronics for FAZIA-INDRA detector upgrade (similar/cheaper and smaller board)

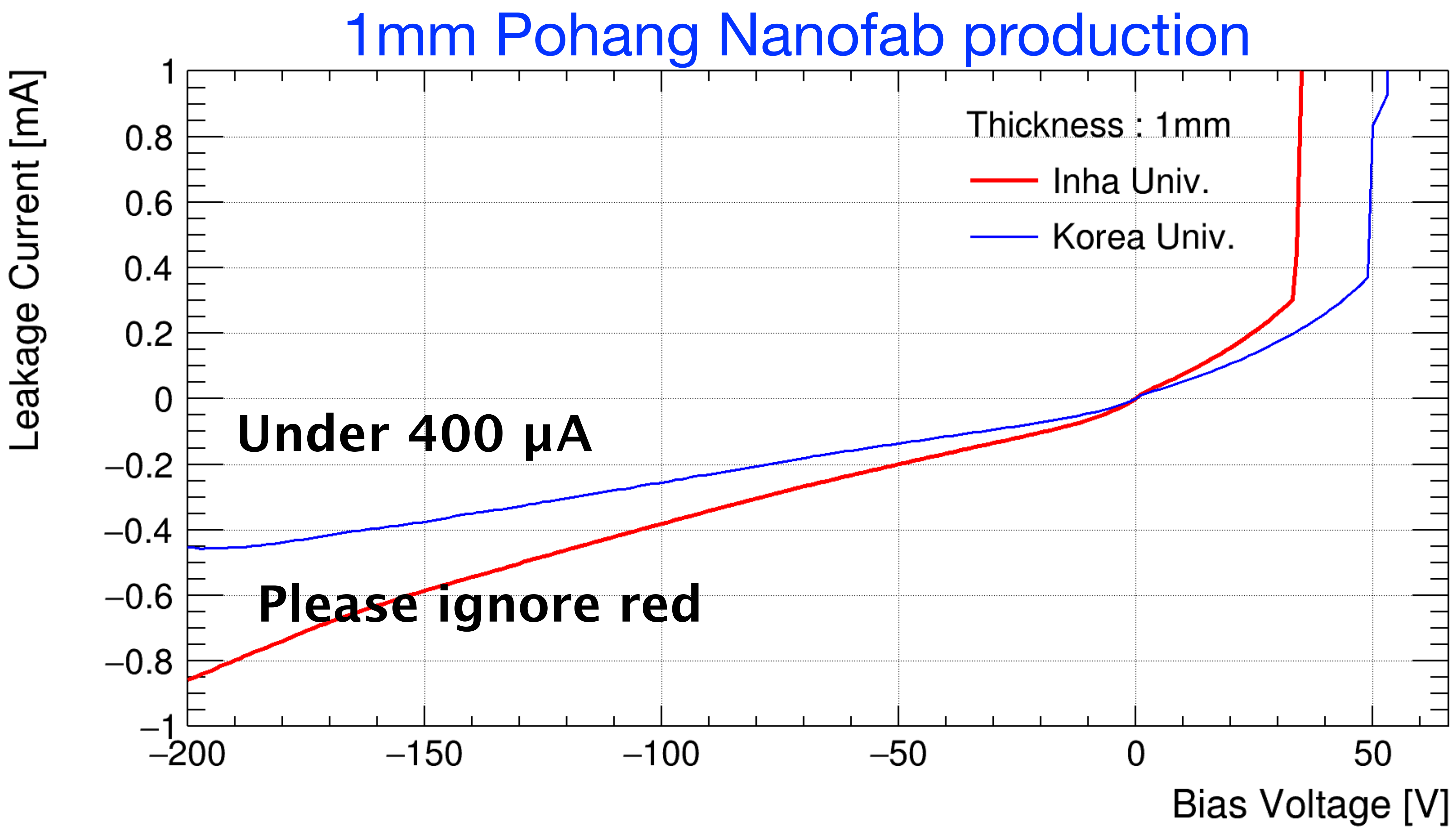
Korean participating Institutes: Inha, Korea, Ewha university supported by CENuM

Leakage current of 750 μm vs. 1 mm



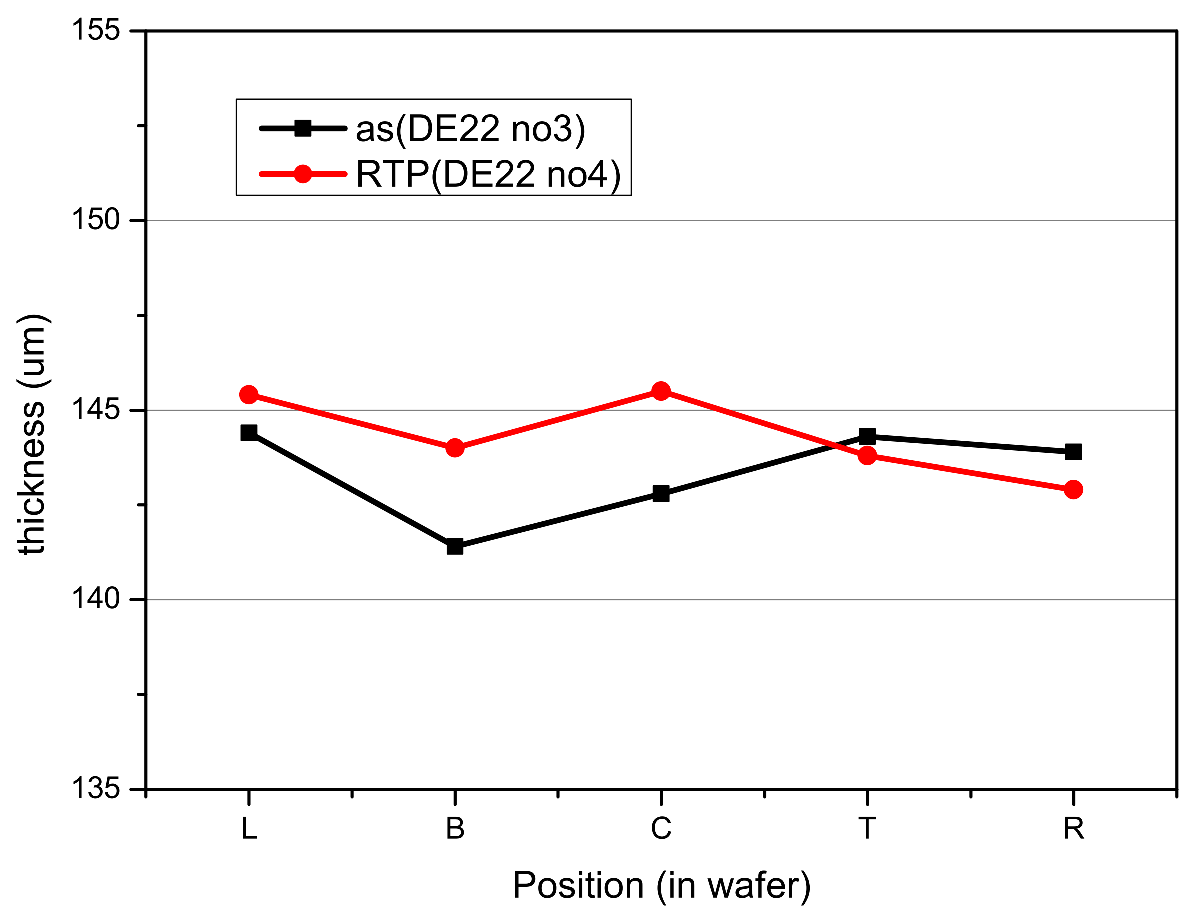
- 1 mm chips were tested (0 ~ 200 V)
  - 750 μm nominal chip: < 25 nA leakage current up to 200 V
  - 1 mm nominal chip: 0.1 mA ~ 1 mA between 50 V ~ 200 V
  - ➡ Doesn't satisfy the qualification

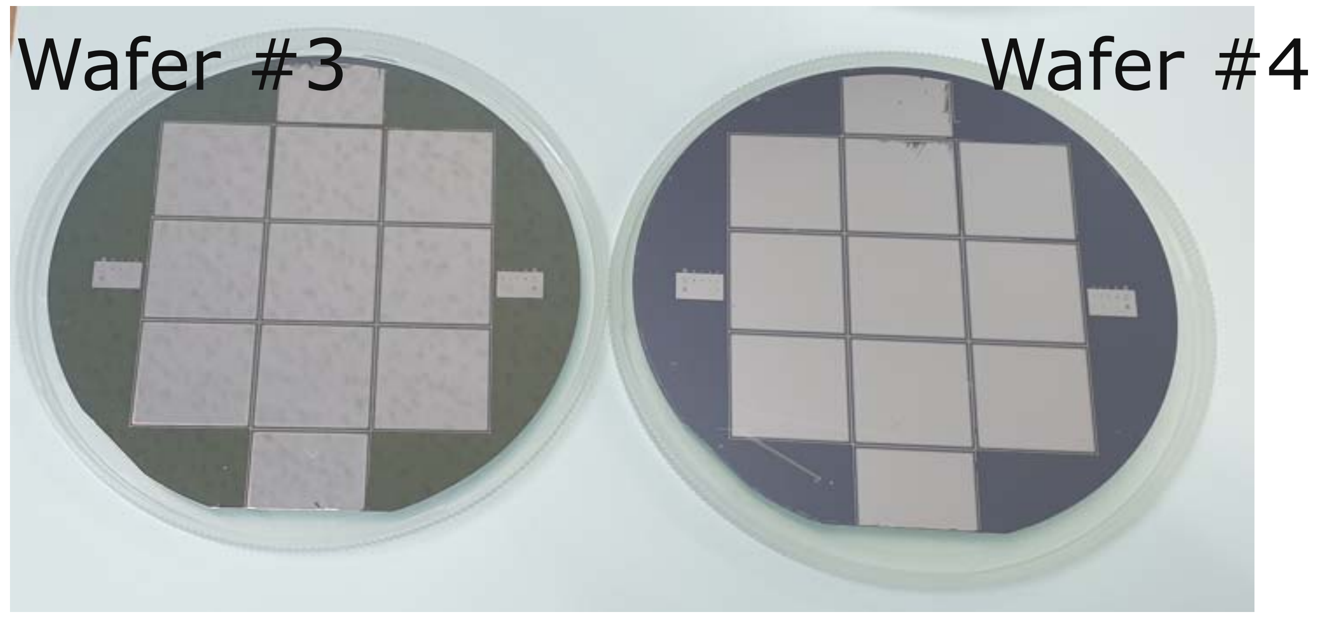


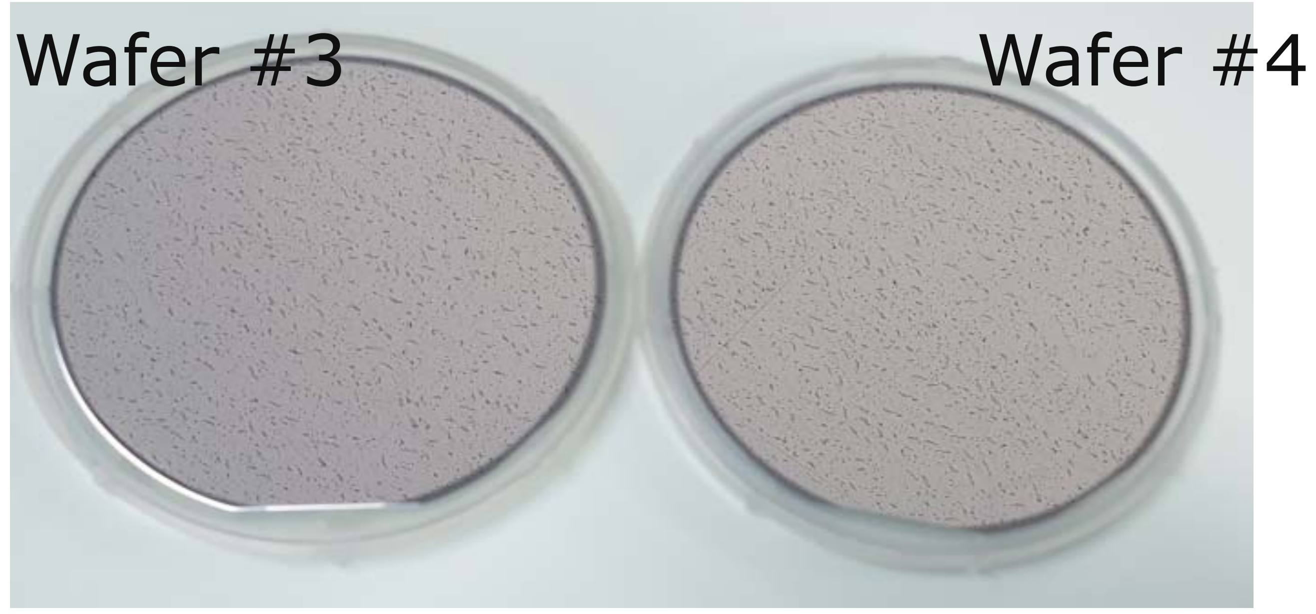


150 µm chip produced :), Jan/2022

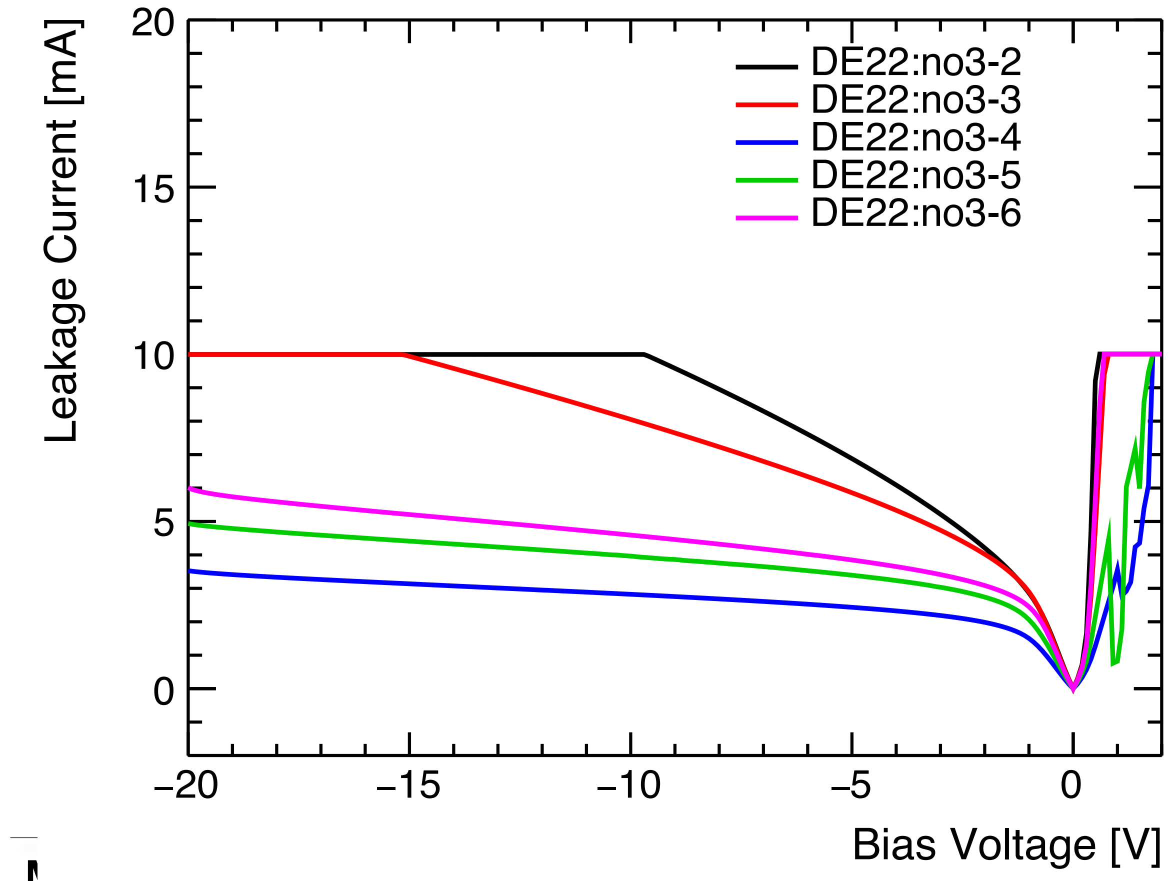
- 300 µm wafer was thinned into 150 µm after the fabrication

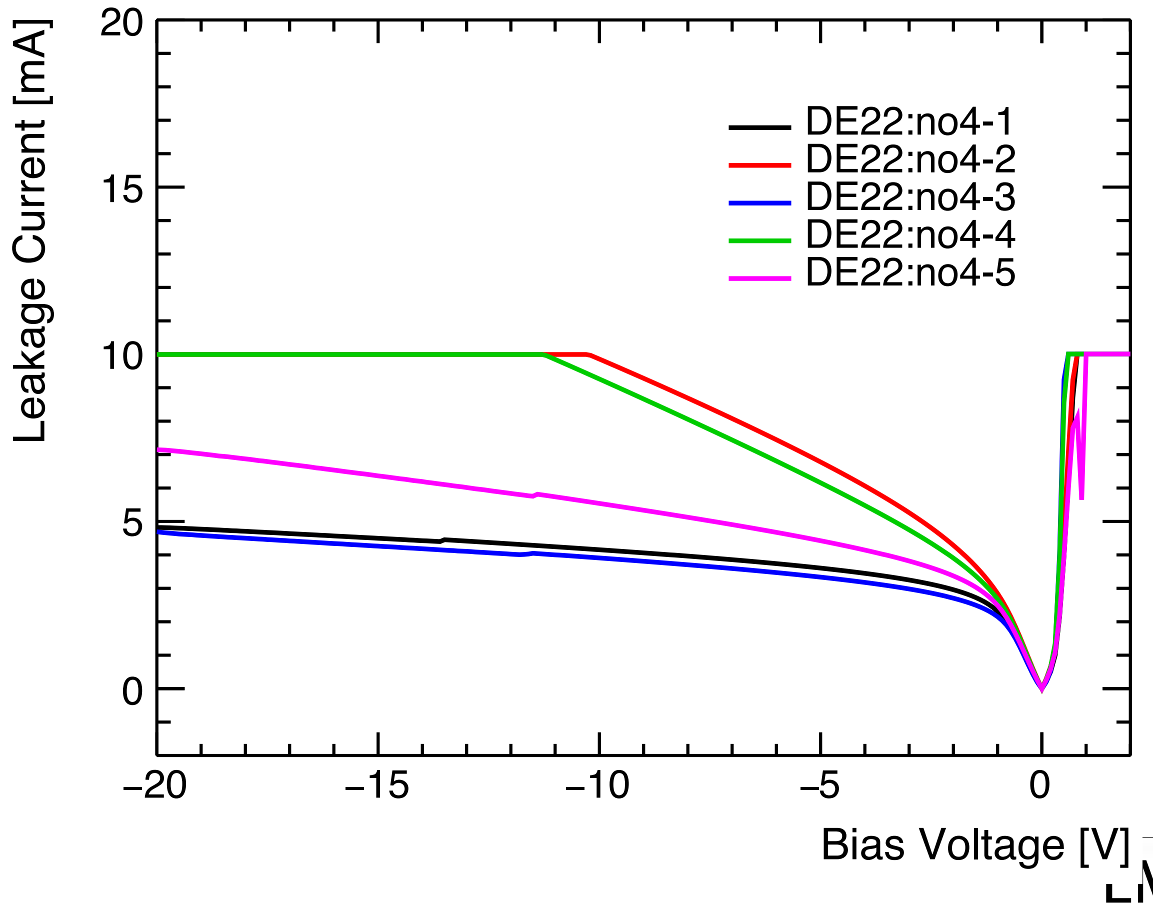






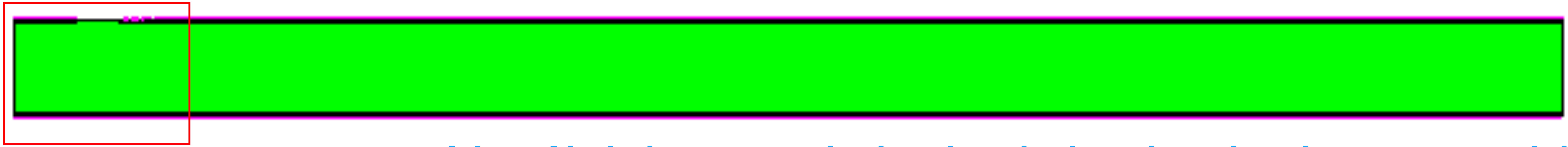
(150um: 5ea) (150um: 5ea)



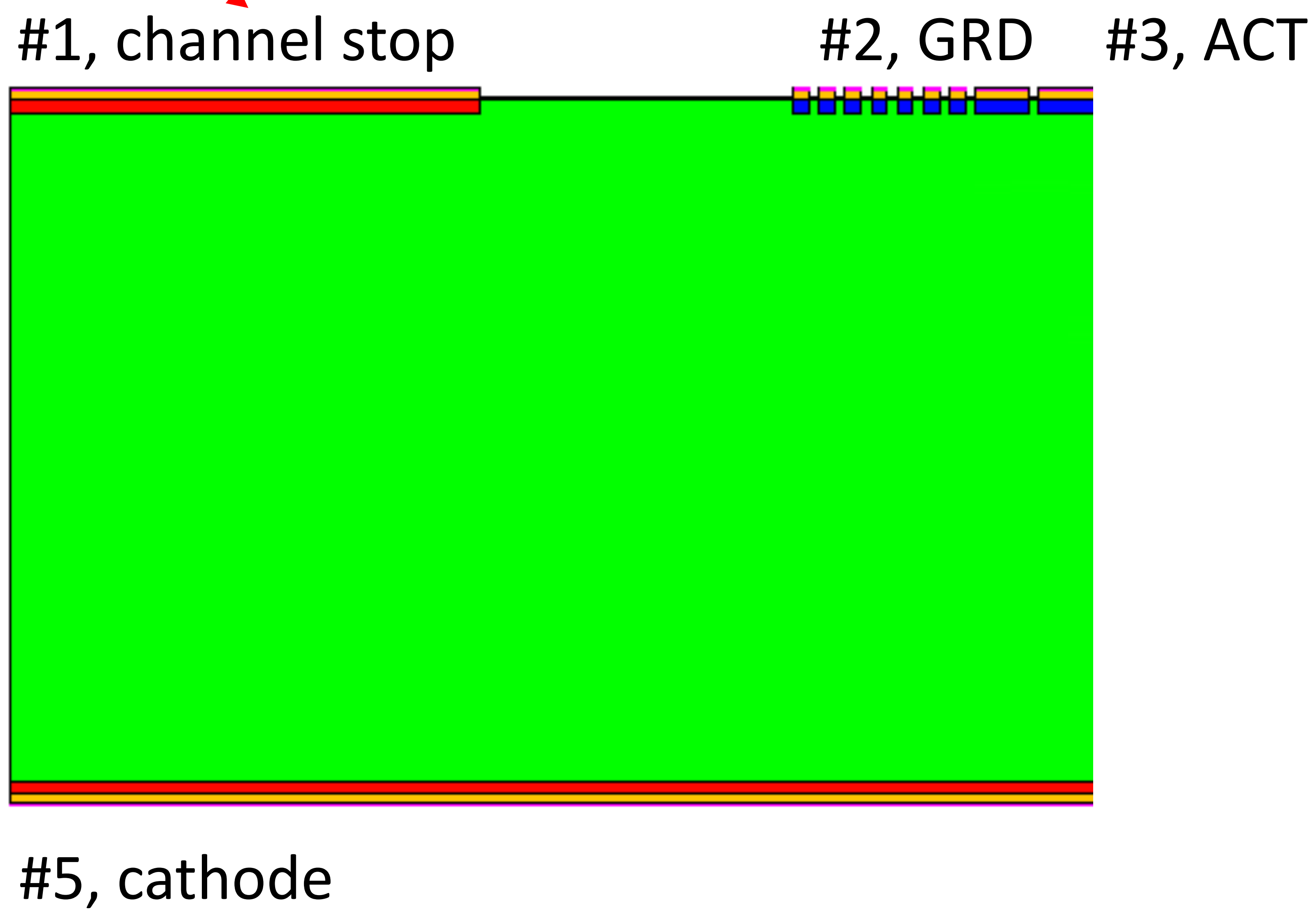


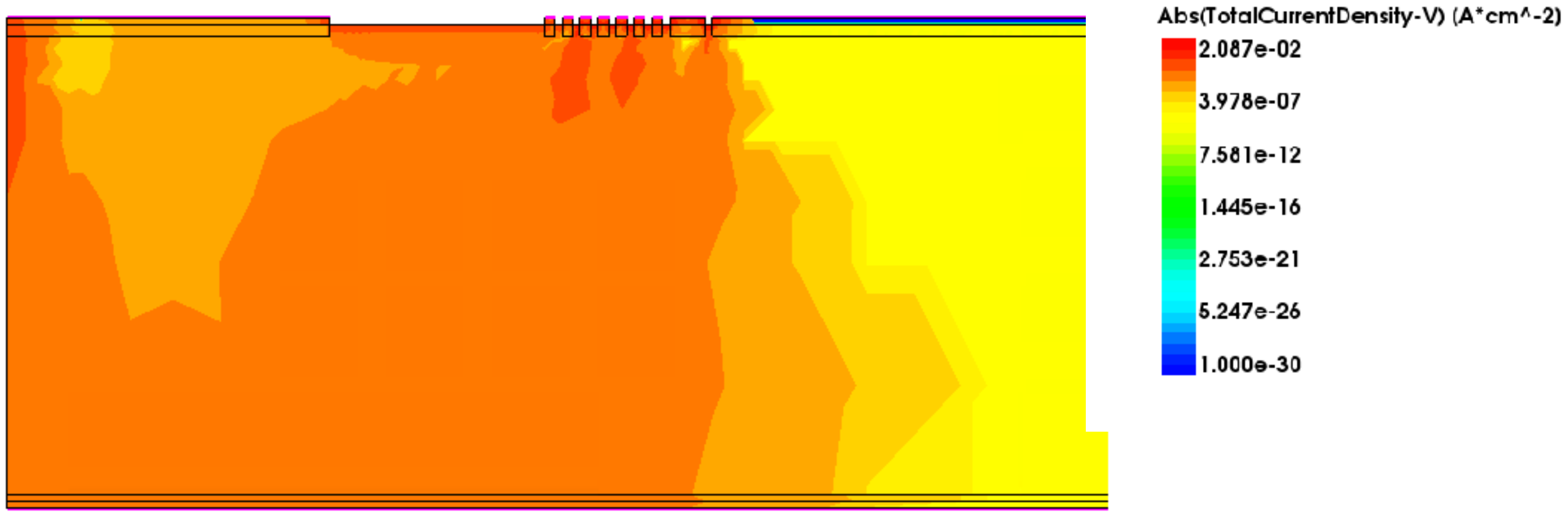
- 150 µm chips also don't satisfy the qualification

Chip design & TCAD simulation (Synopsys)



A lot of help by experts in the electrical engineering department at Inha

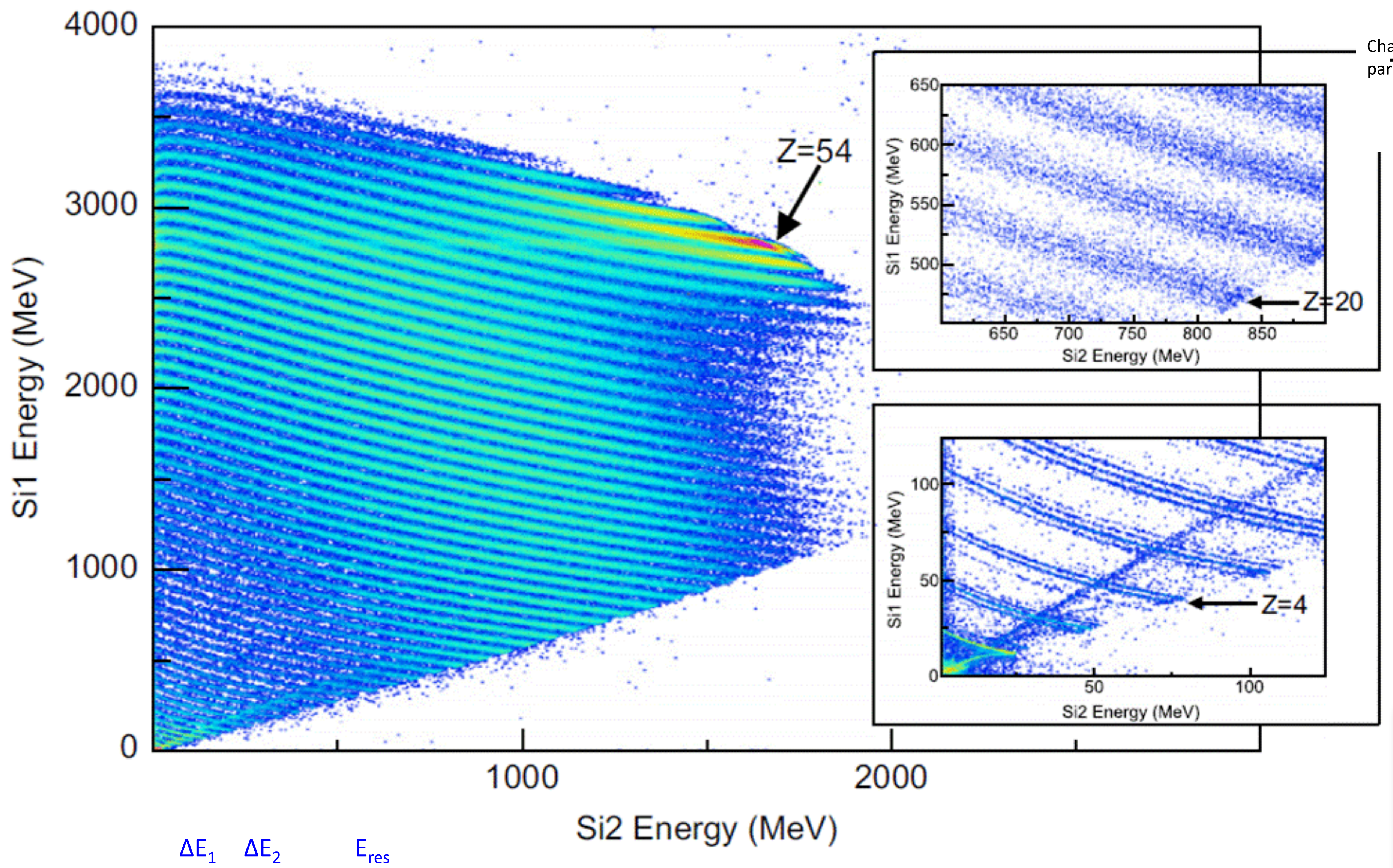


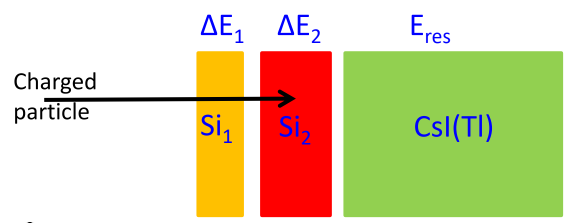


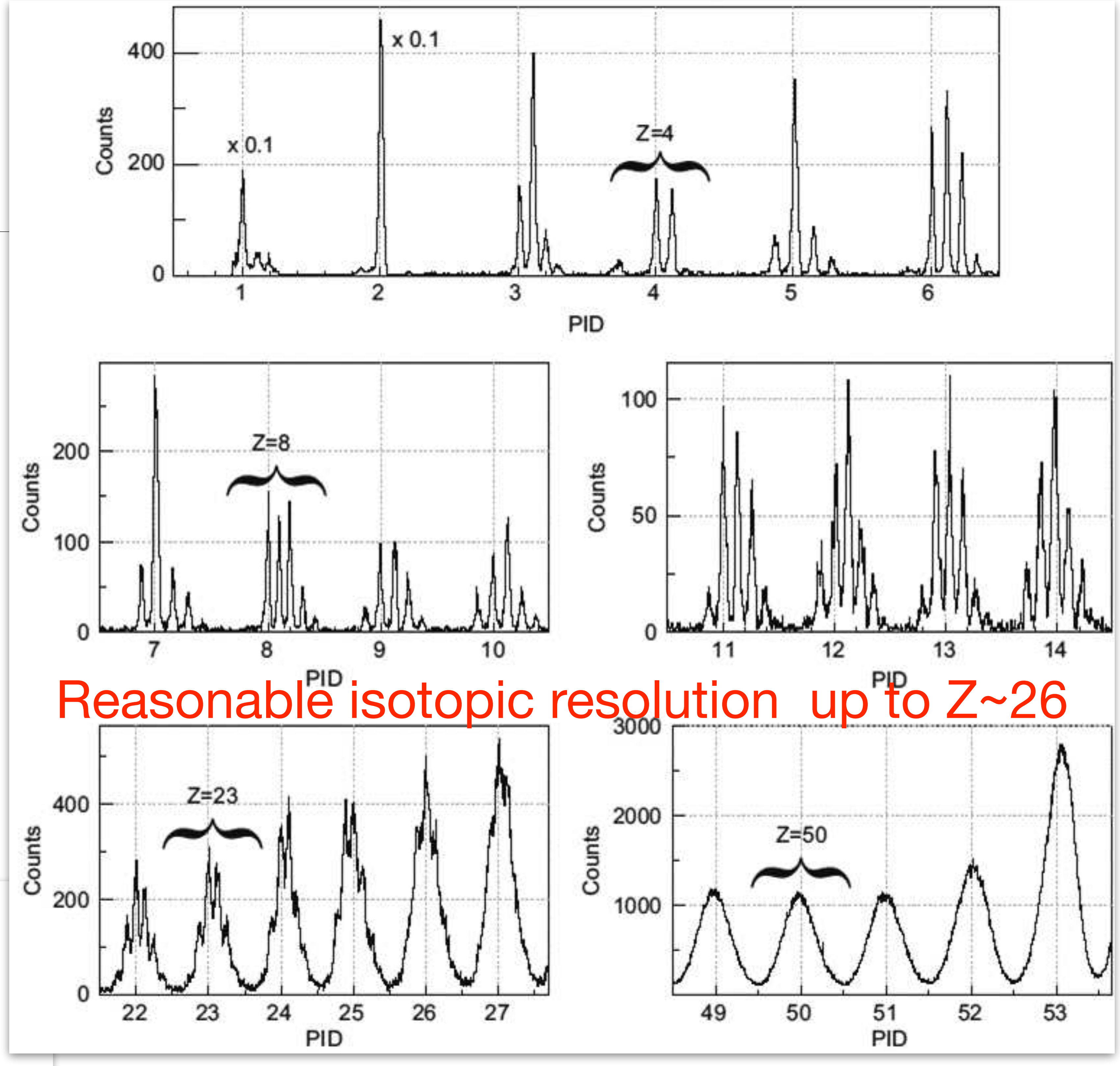
2D simulation on a side region of the chip
Current density distribution from 2D simulation

Structure, dimensions
Doping profile…. & ion-implantation energy, dose, incident angles ….

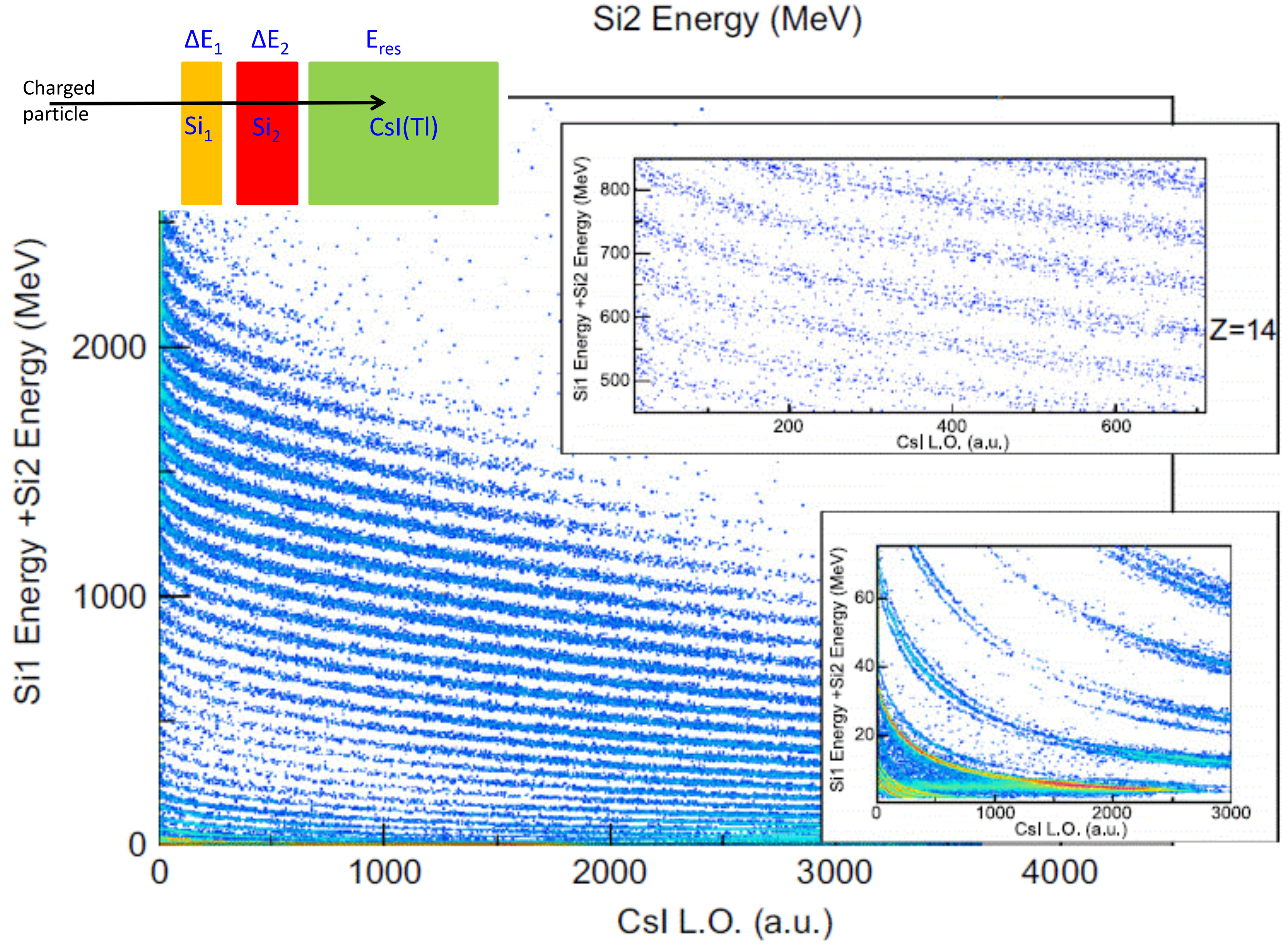
FAZIA PID performance

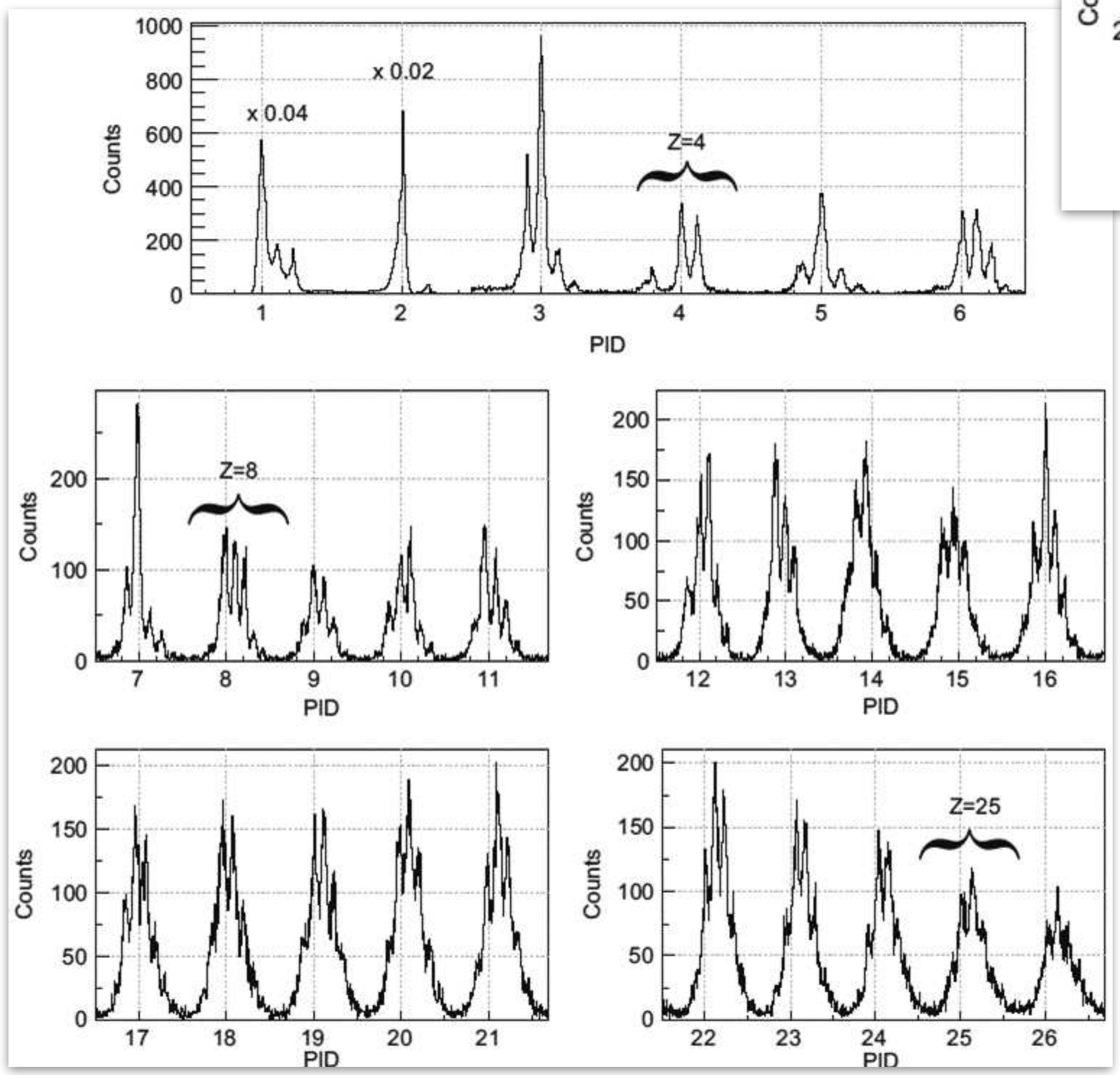






Reasonable isotopic resolution up to Z~26



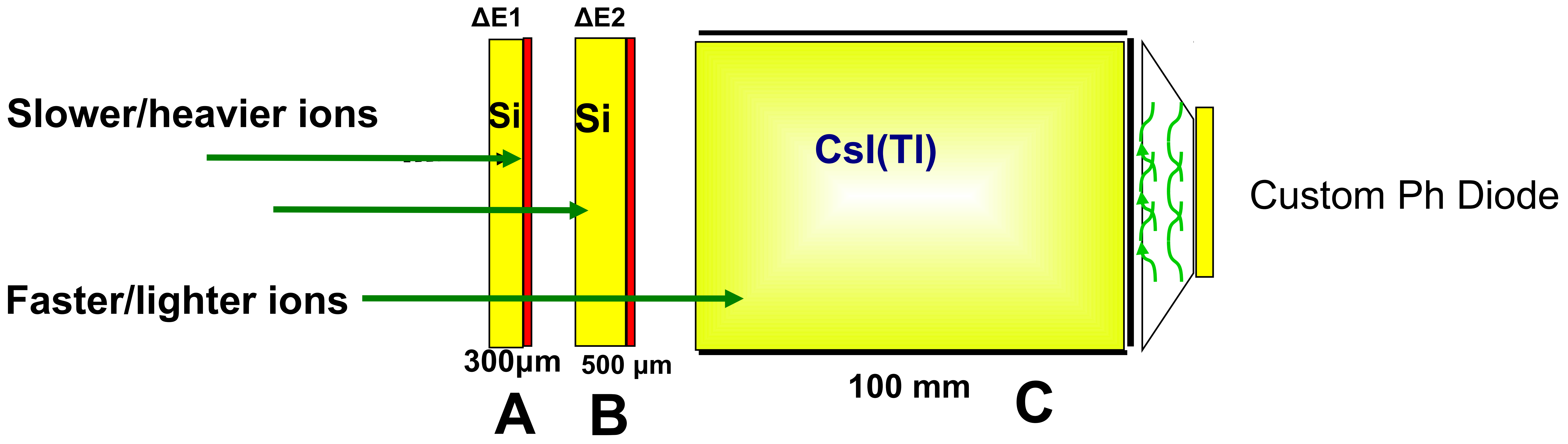


for Z = 6

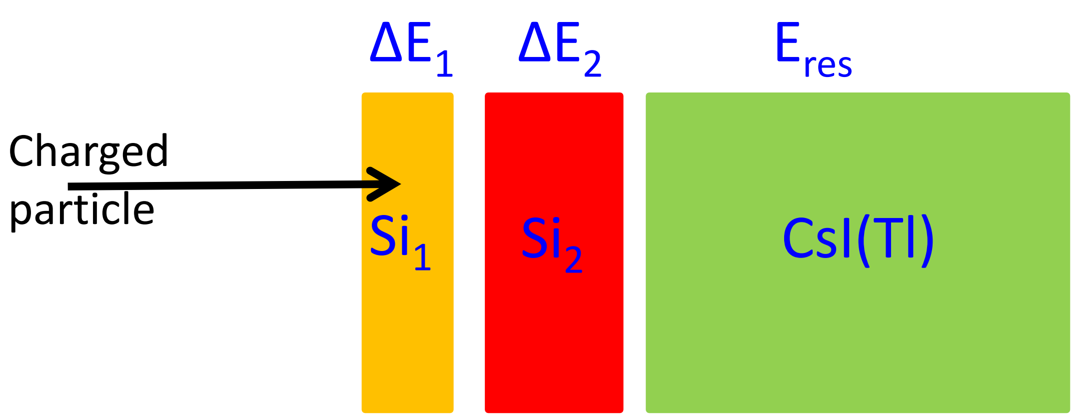
- **charge identification from 2 MeV/u**
- **isotopic discrimination from 5 MeV/u**

Eur. Phys. J. A (2014) 50: 47

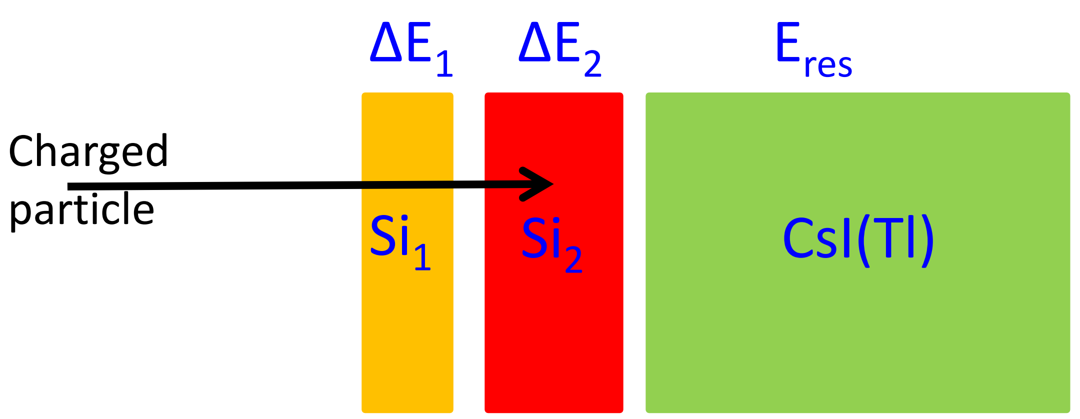
The FAZIA telescope



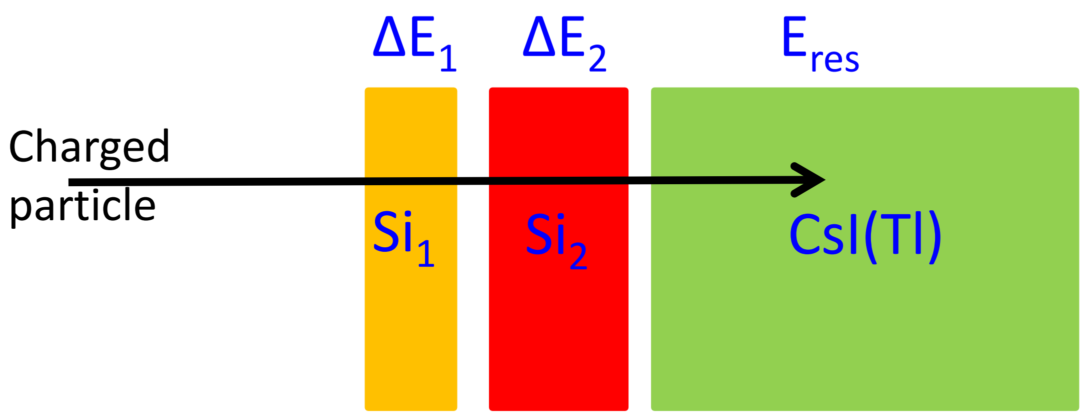
Pulse shape for stopped particles



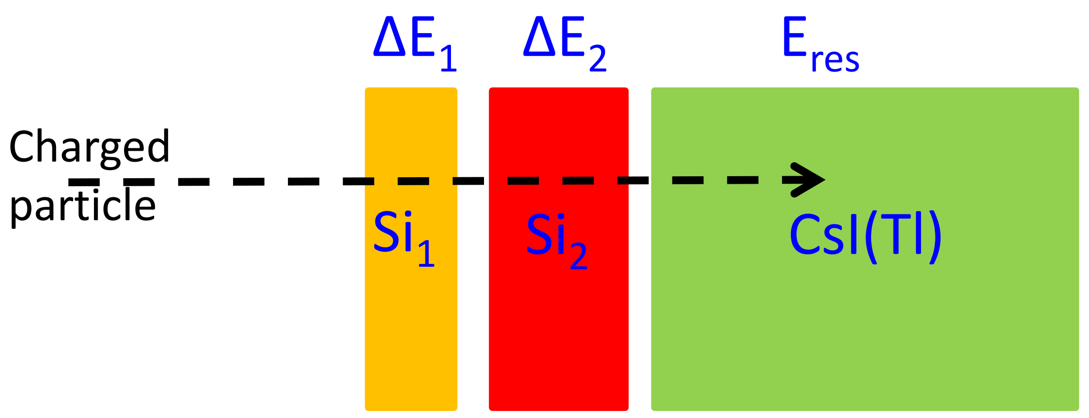
ΔE-E method



ΔE-E method



Pulse shape for energetic particles



Identification threshold
~ 50 µm penetration

Korea in FAZIA: Brief history

Description of prof. Hong

Before 2019

- The Korean group (part of LAMPS Collaboration) was designing the Si-CsI telescope detector for the low-energy (a few tens MeV per nucleon) nuclear collision experiments at RAON.
- The International Advisory Committee of RAON reviewed the status of the detector development and suggested us to collaborate with FAZIA in Europe, because it had been operating the most advanced Si-CsI detector system for nuclear physics.
- Therefore, to join the Collaboration, we started the discussion with some FAZIA members in several Conferences & meetings

In 2019

- Even before officially joining the FAZIA Collaboration, a group of interested Korean researchers visited GANIL in May 2019 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 and presented the application to join the Collaboration.

Then, MOU in 2020

Addendum of MOU for FAZIA, adding Korea with CENuM (Center for Extreme Nuclear Matters directed by B. Hong) the national representative, was signed by CENuM (Korea), INFN (Italy), CNRS/IN2P3 (France), GANIL (France), COPIN (Poland), UHU (Spain) on November 6, 2020.