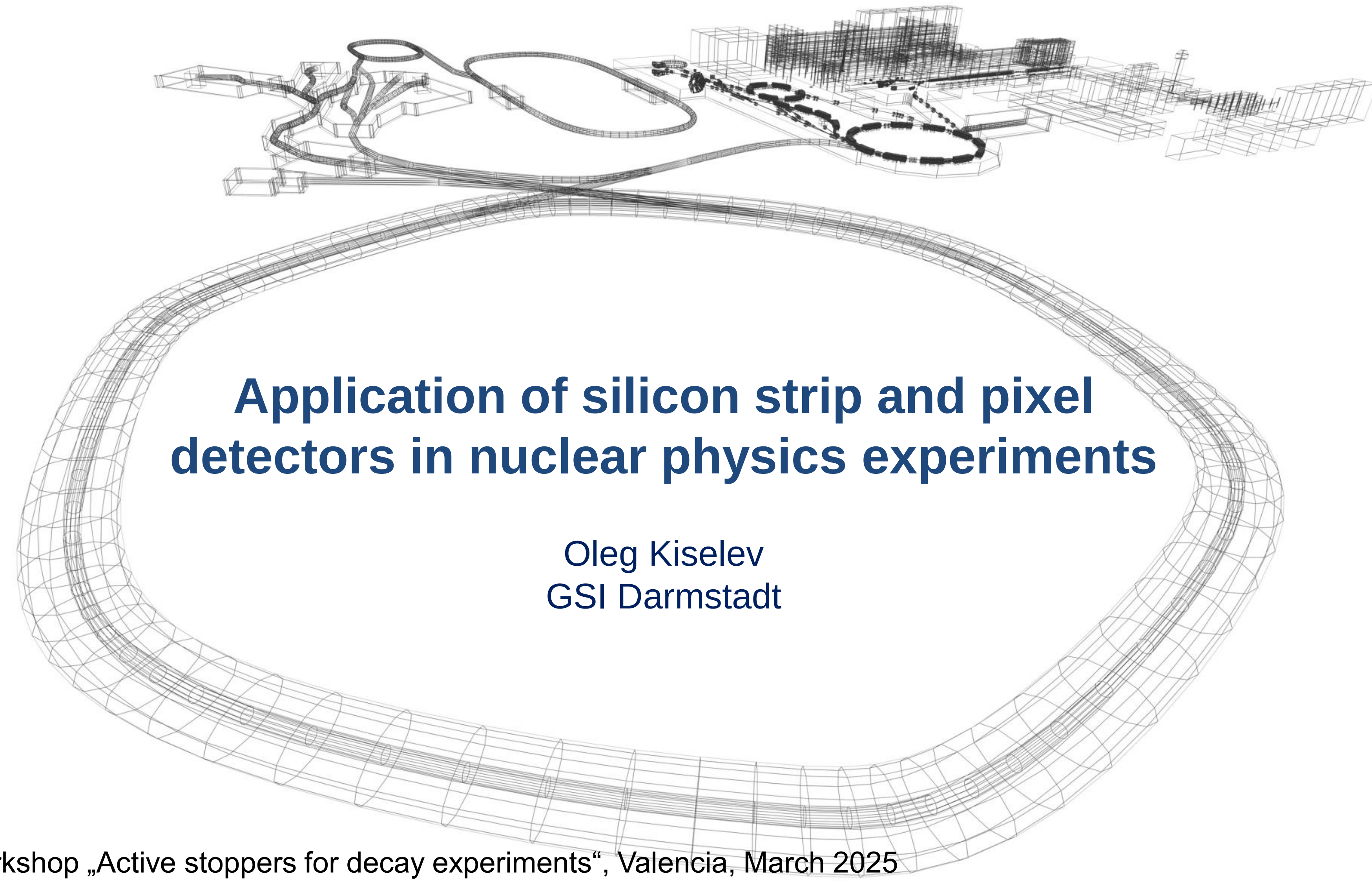
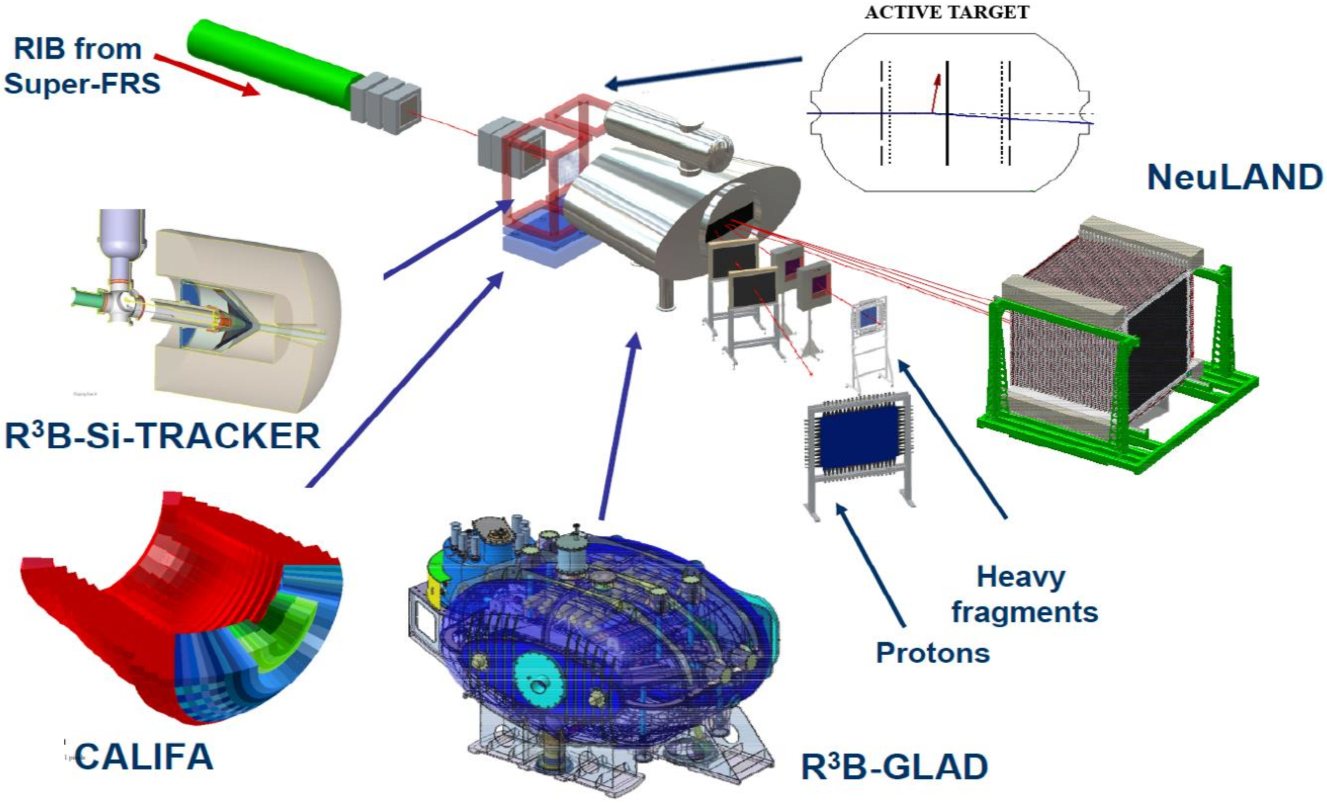


Application of silicon strip and pixel detectors in nuclear physics experiments

Oleg Kiselev
GSI Darmstadt

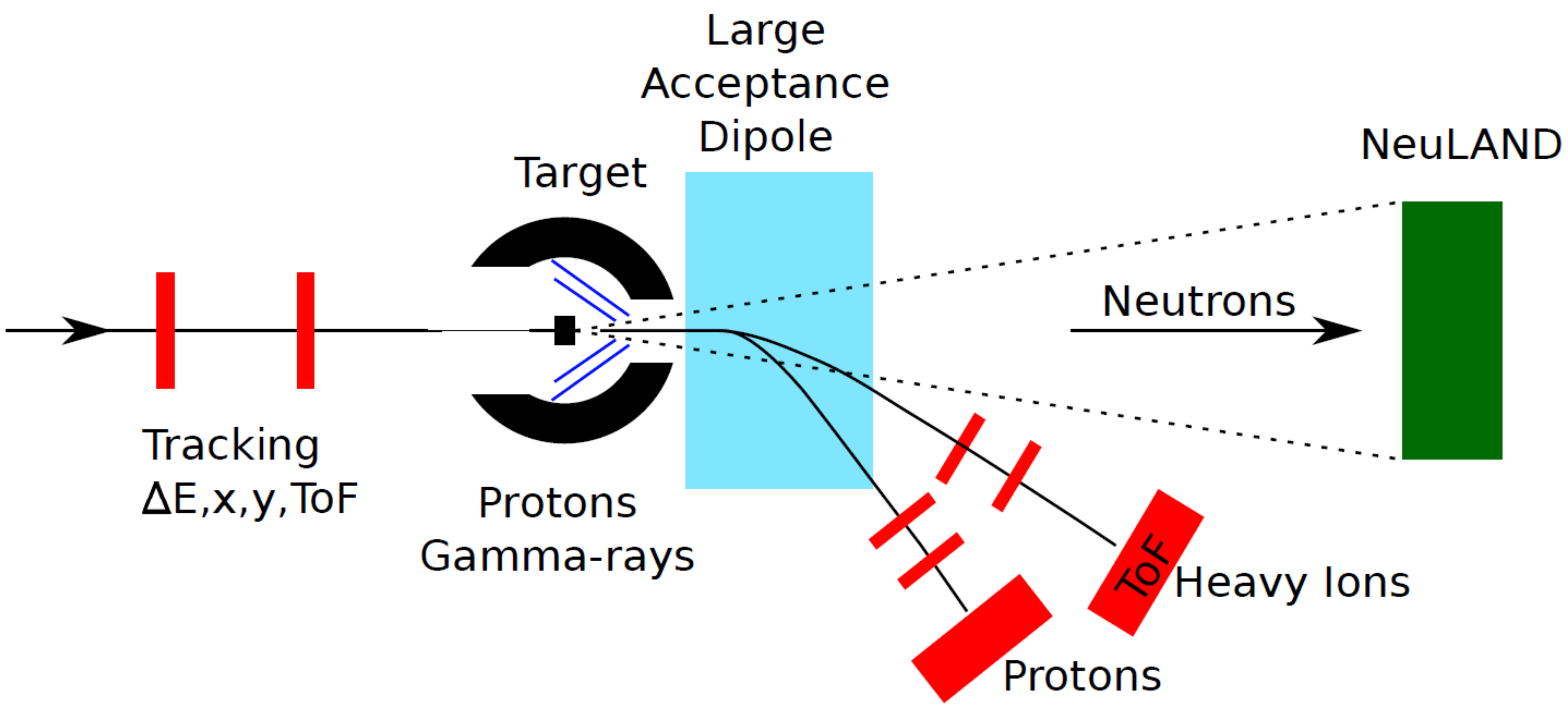
Workshop „Active stoppers for decay experiments", Valencia, March 2025

R3B (Relativistic Reactions with Radioactive Beams)



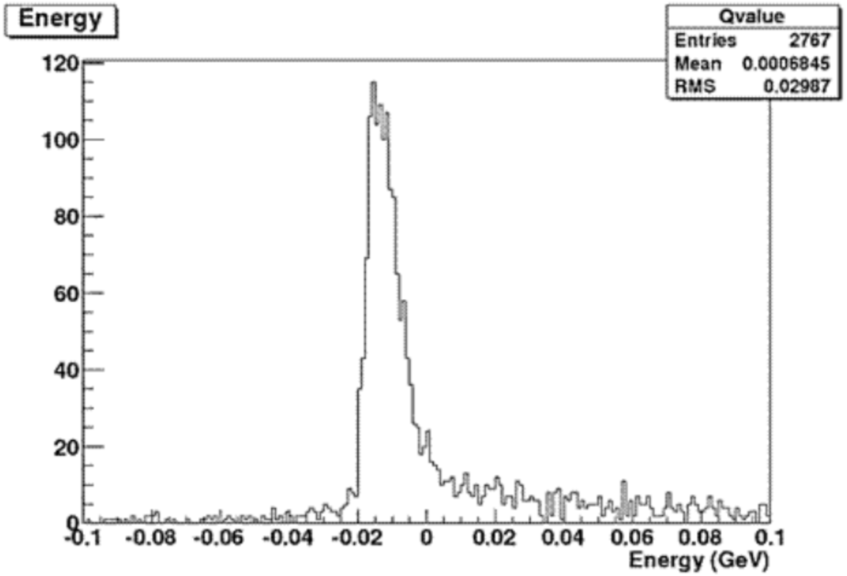
- The aim of the R3B collaboration is to construct a versatile experimental setup and perform experiments using relativistic radioactive beams across the full energy range available at FAIR
- The experimental assembly is designed to conduct kinematically complete nuclear reactions in inverse kinematics with fixed-targets

Typical scheme of R3B experiments

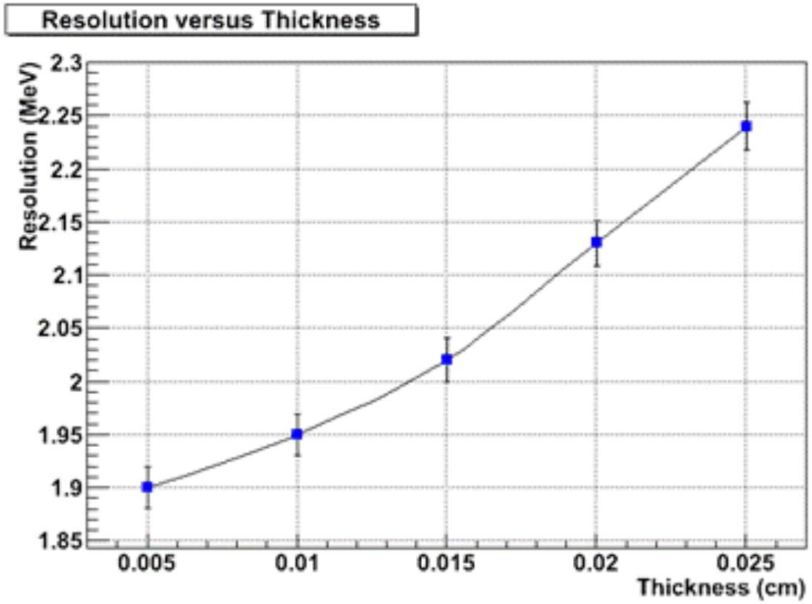


- The target region is surrounded by the silicon tracker (blue lines) and a CALIFA calorimeter (black)
- Neutrons are detected by NeuLAND (green)
- Beam-like particles are tracked before and after the dipole magnet by an array of detectors (red)

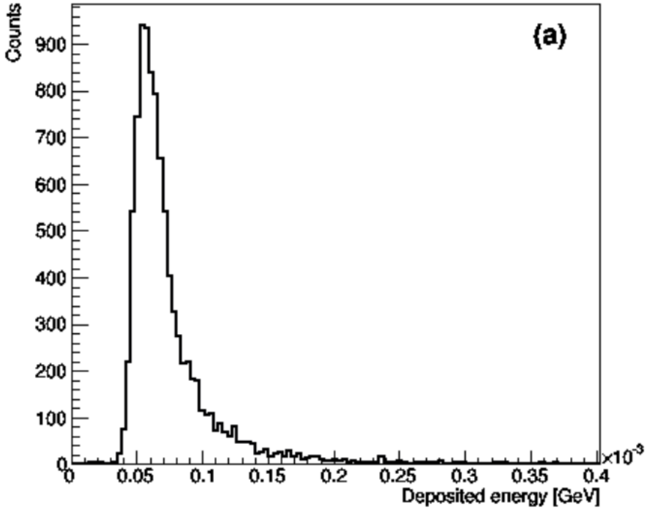
Requirements for recoil system



Q resolution $^{12}C(p,2p)^{11}B$ @400 MeV
Q_{ex} = 5 MeV
Full CALIFA

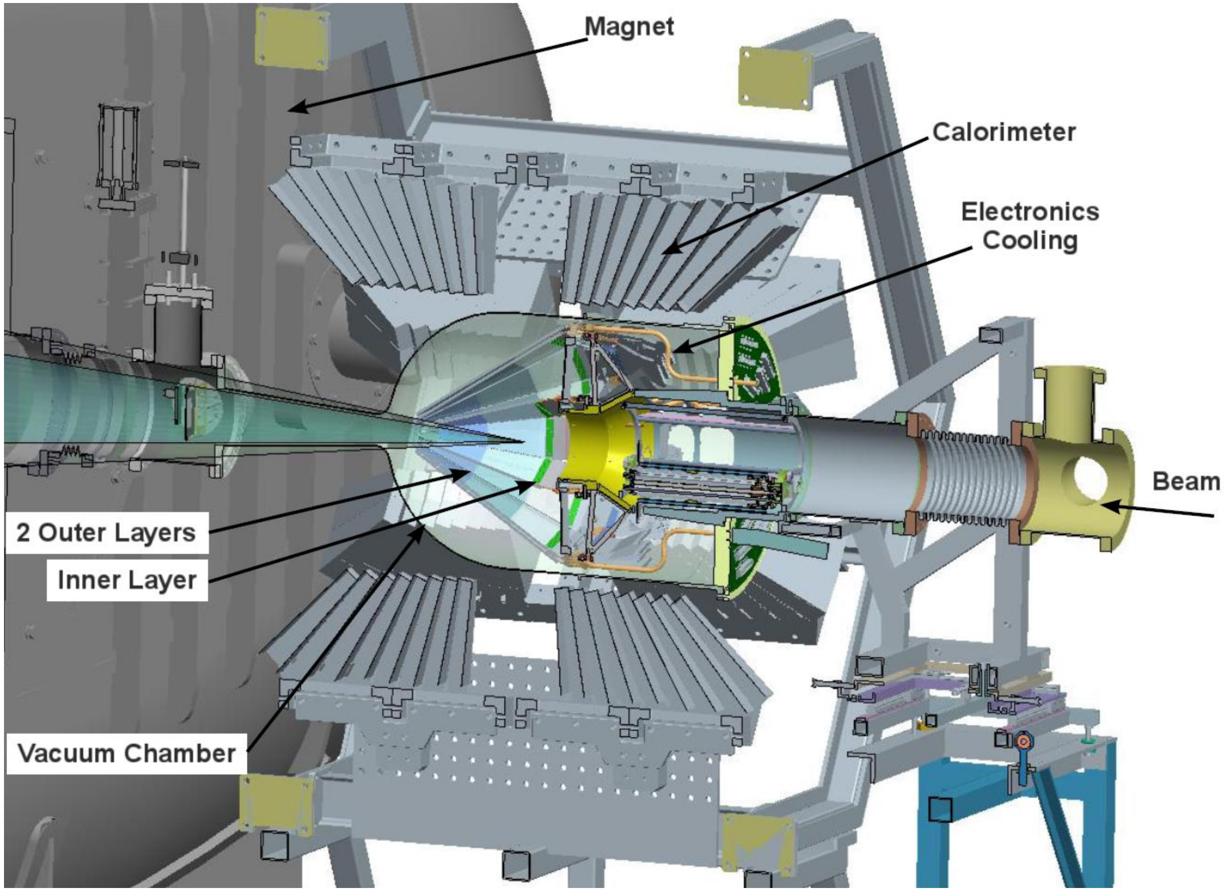


- *Elastic/inelastic and quasi-elastic scattering*
- *E = 300 – 700 MeV*
- *2-3 layers, vertex determination (1-2 mm)*

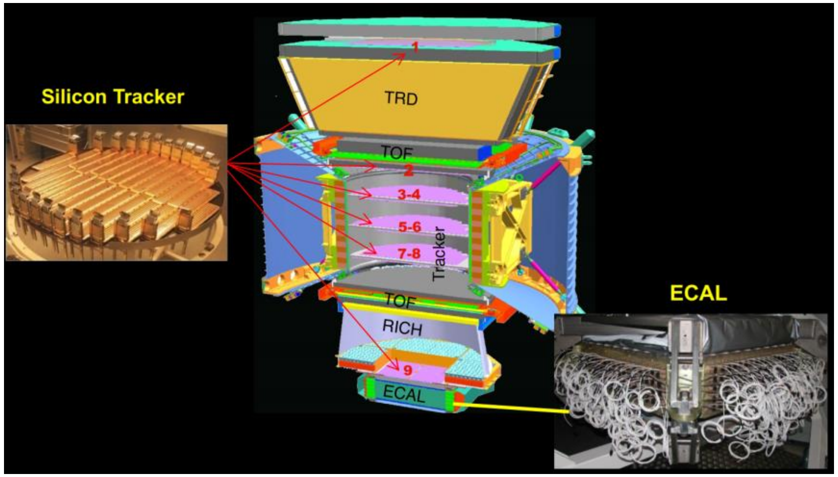


Requirements for recoil system

- Hit rate up to 5 kHz/ch
- First layer 50-100 μm, second 300 μm thick
- Low energy threshold 40 keV
- Strip size 50-100 μm
- No heating of the liH_2 target
- Minimum material in the theta angles ≤90°

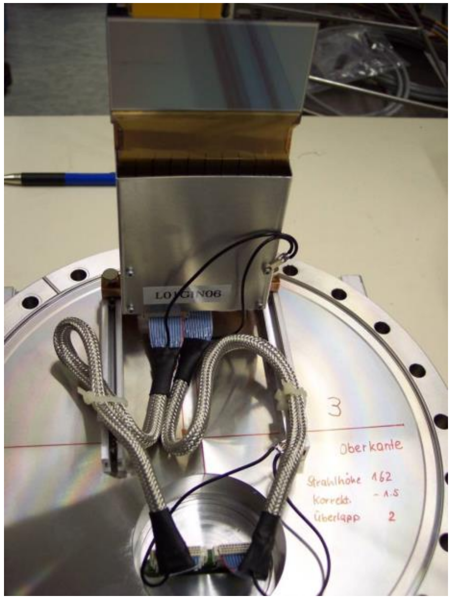


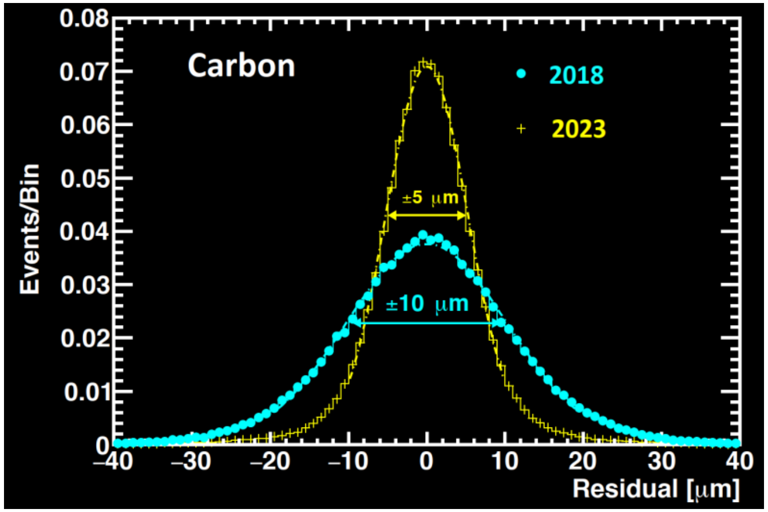
First attemps of building recoil tracker



- Development of the Si strip detectors is very complex, long and expensive task
- By chance, there was just finished development fitting our needs
- Several m^2 of silicon tracker for space application

AMS Si strip detectors



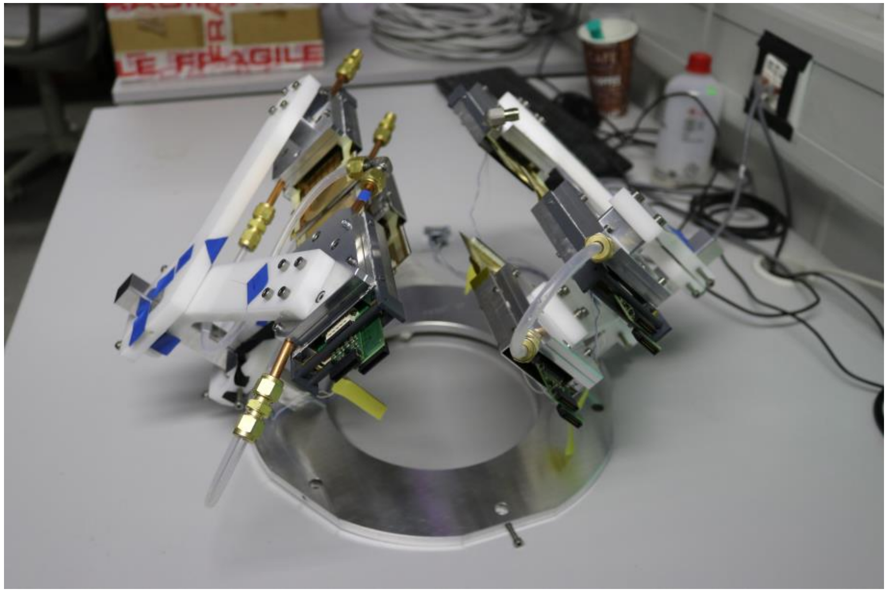


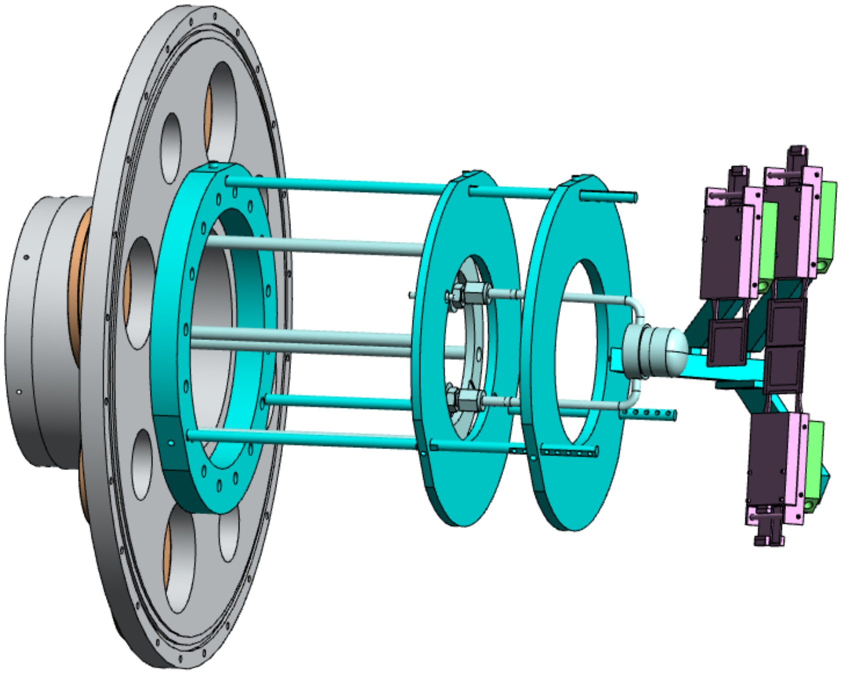
AMS data

- Double-sided Si microstrip detectors
- Area 28 cm^2, 300 µm thick, 100 µm strip pitch
- Energy resolution ~1%
- Dynamic range – from p to Fe ions
- Very low energy dissipation of FE electronics - works in vacuum without active cooling
- 1024 channels, multiplexed readout (trigger rate up to 2.5 kHz)
- Position resolution ~40 µm for protons, 10-15 µm for ions

Implementation and readout done at GSI

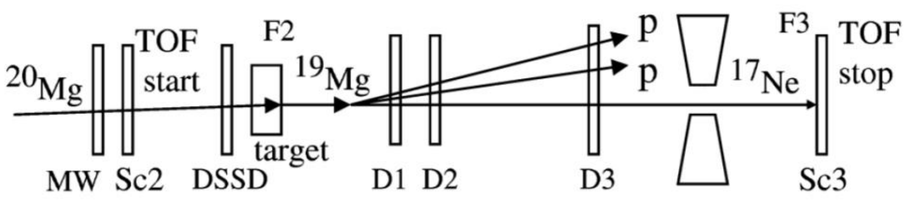
Recoil tracker R3B



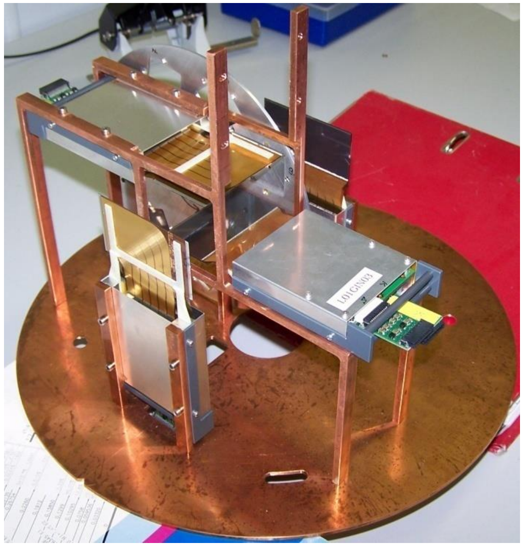


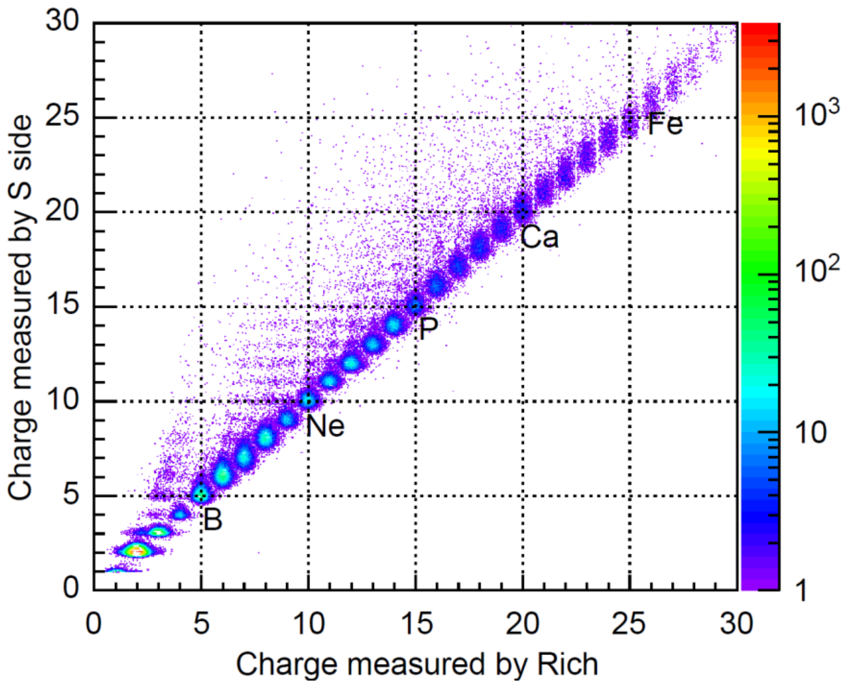
- Two-arm design for the experiments in Cave C
- Reactions like (p, 2p), (p, p’), (p, pn)
- 6 AMS detectors around liH_2 target
- Solid angle (~20%) for p, 2p reactions

Precise tracking + spectroscopy



Several experiments at FRS, tracking of ions + protons

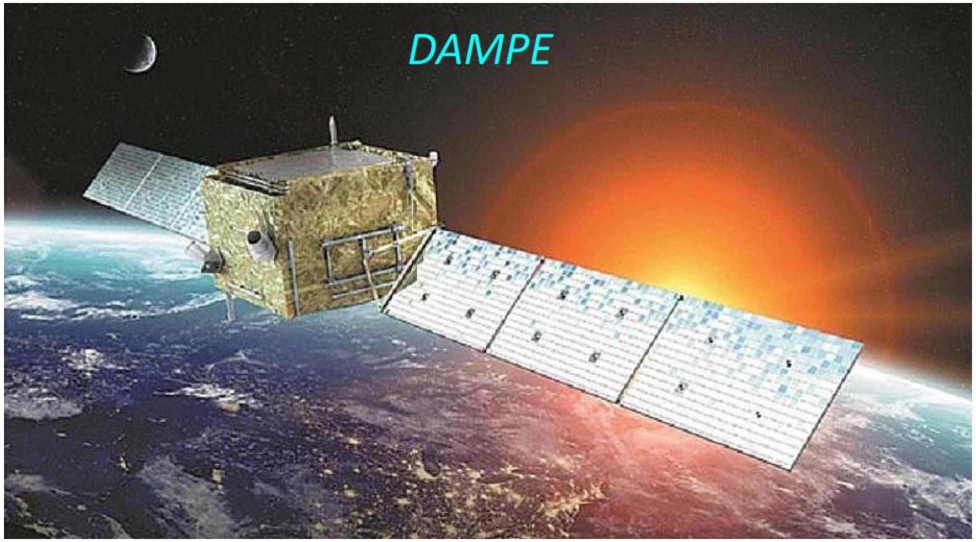


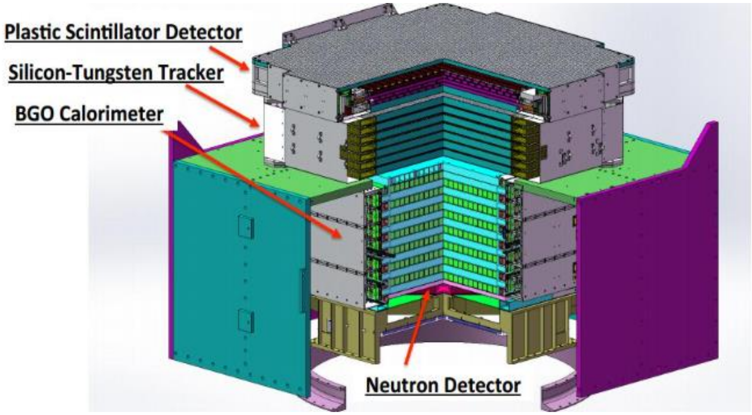


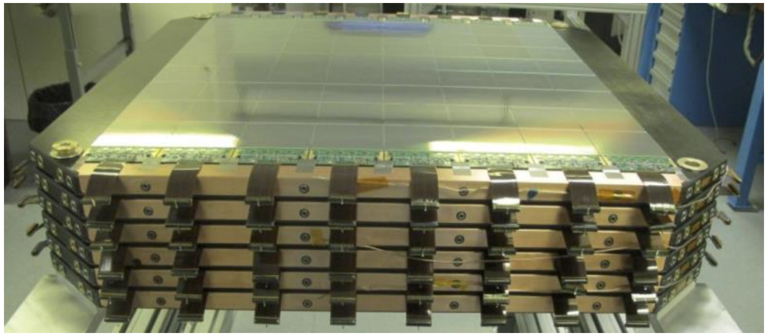
Si – RICH correllation (AMS data)

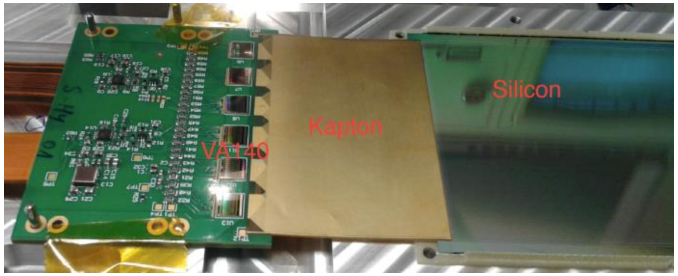
- ***Key to success*** of 2p-radioactivity measurements at FRS and R3B QFS experiments
- Forward tracking and recoil tracker configurations

New microstrip detectors – DAMPE mission





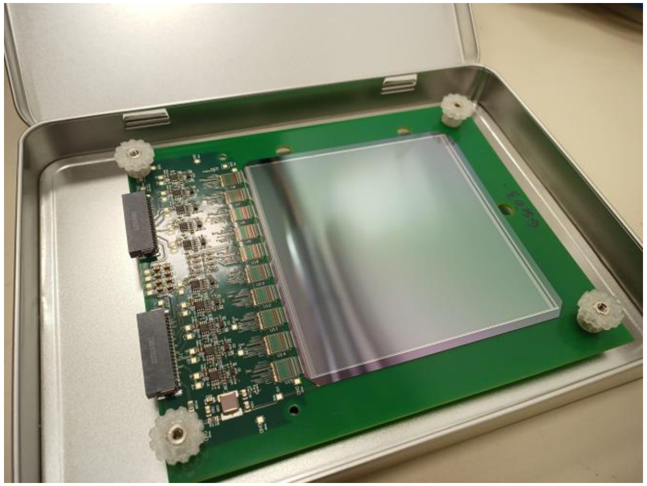


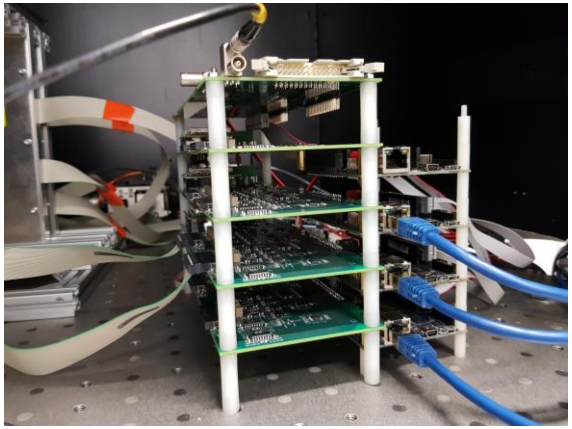


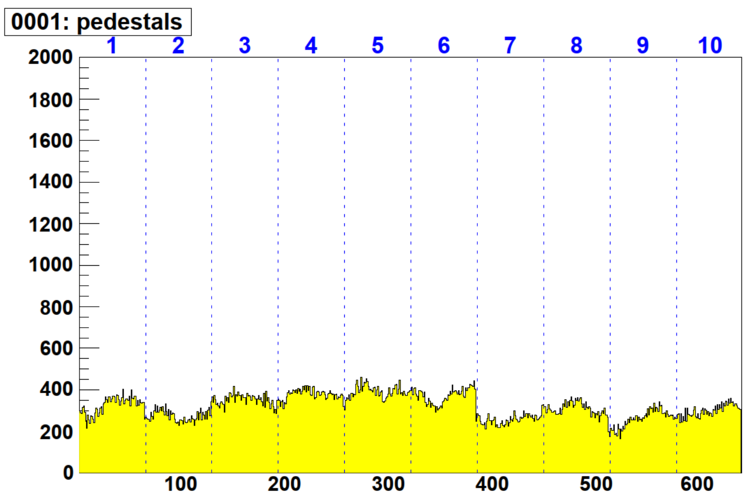
- ✓ New detectors designed for DAMPE mission in space by Hamamatsu / INFN Perugia
- ✓ 9.5 x 9.5 cm, single-sided, 320 µm thick, 121 µm strip pitch
- ✓ Same front-end ASICs as AMS detectors
- ✓ Different solutions for the readout and integration

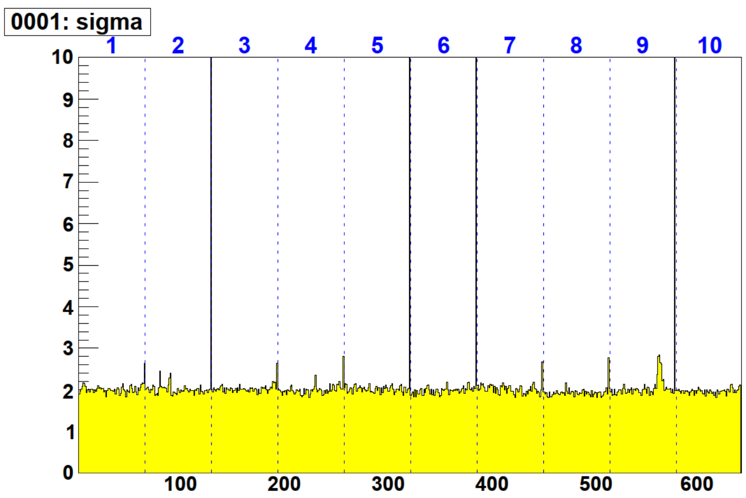
Further development of microstrip detectors - FOOT

- ✓ New detectors designed for FOOT experiment by Hamamatsu / INFN Perugia
- ✓ 10 x 10 cm, single-sided, 150 µm thick, 150 µm strip pitch
- ✓ Same front-end 64ch ASICs as of DAMPE detectors – IDE1140 (IDEAS)
- ✓ Dynamic range -200 fC - +200 fC
- ✓ 640 channels per detector, multiplexed readout
- ✓ New FPGA-based DAQ system, formfactor-free
- ✓ Trigger rate up to 5 kHz









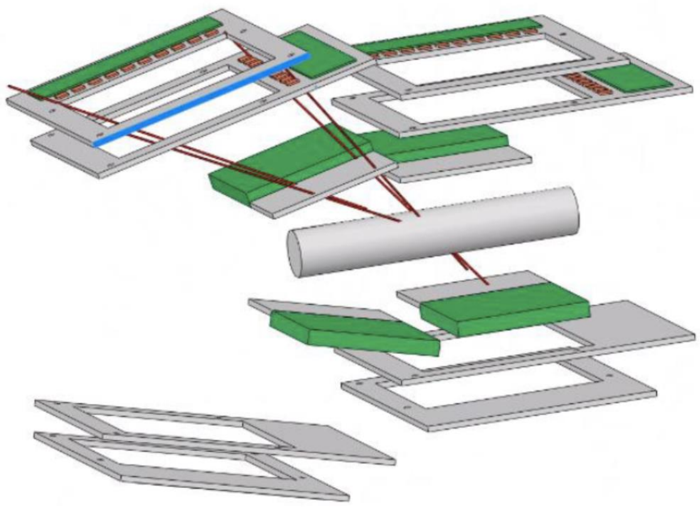
- The front-end board is changed with respect to original FOOT – twice higher trigger rate possible
- Firmware for the FPGA is changed – synchronization trigger and time stamp added
- Completely new readout software

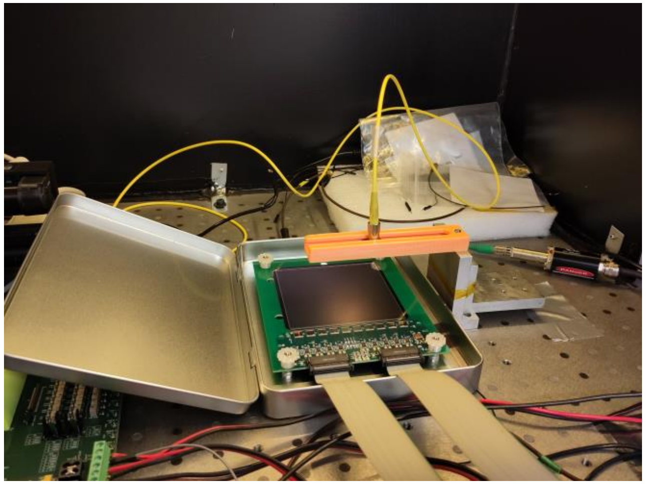
12bit ADC / 4096 ch
Noise 2 - 2.5 ch

Fully different implementation as by FOOT collaboration

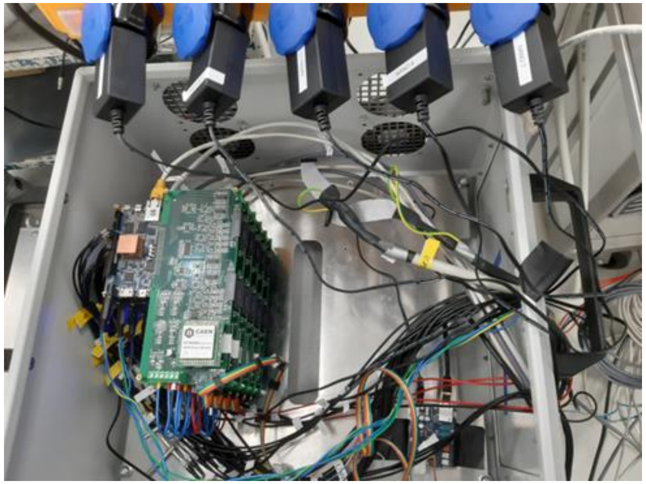
FOOT-based recoil tracker for R3B

- ✓ 10x10 cm detectors allow much higher solid-angle coverage for (p, 2p) reactions
- ✓ Will be used in pairs providing X-Y measurements
- ✓ Longer liH_2 target can be used increasing the event rate

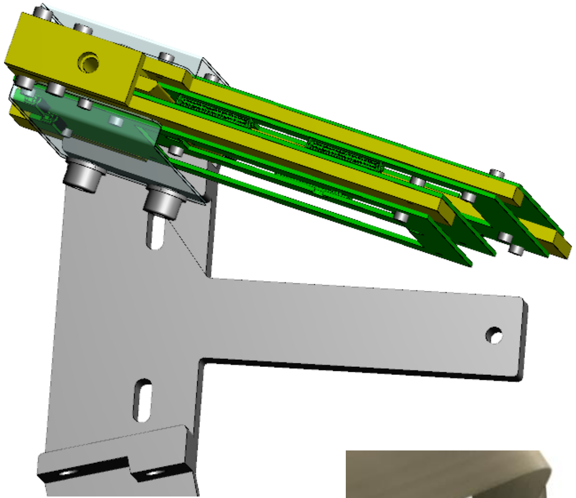


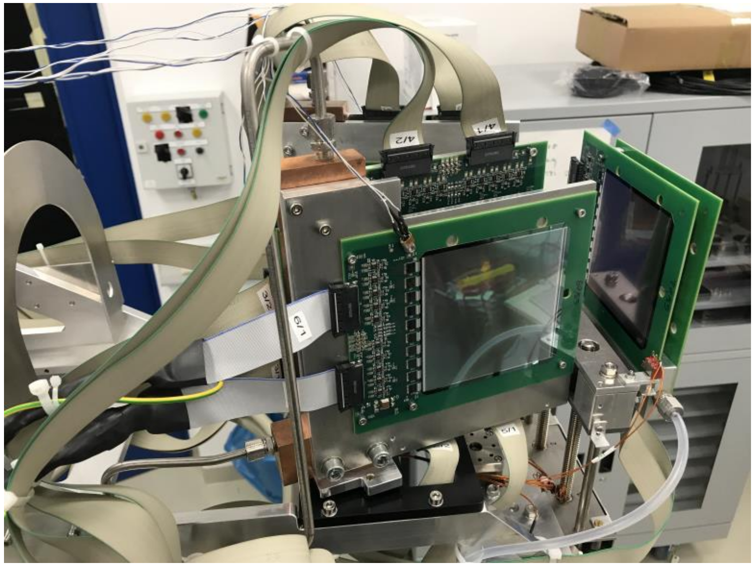


Test of the FOOT detectors using IR laser



FOOT-based recoil tracker for R3B

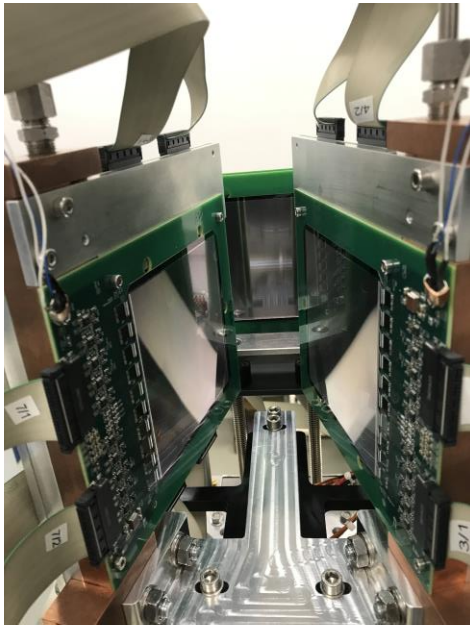


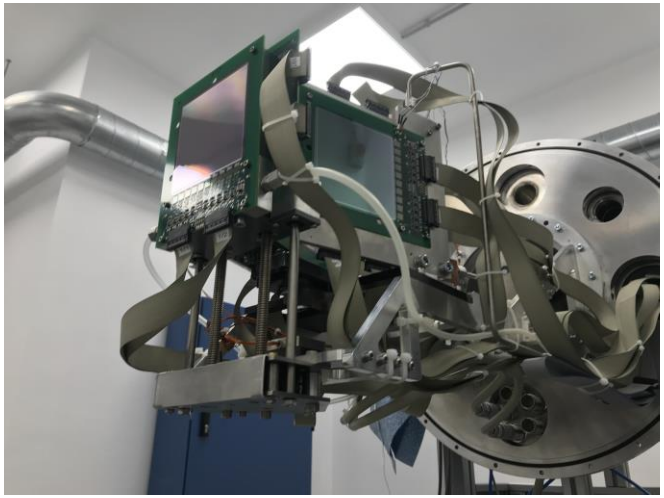


Two-arm tracker for protons/alphas

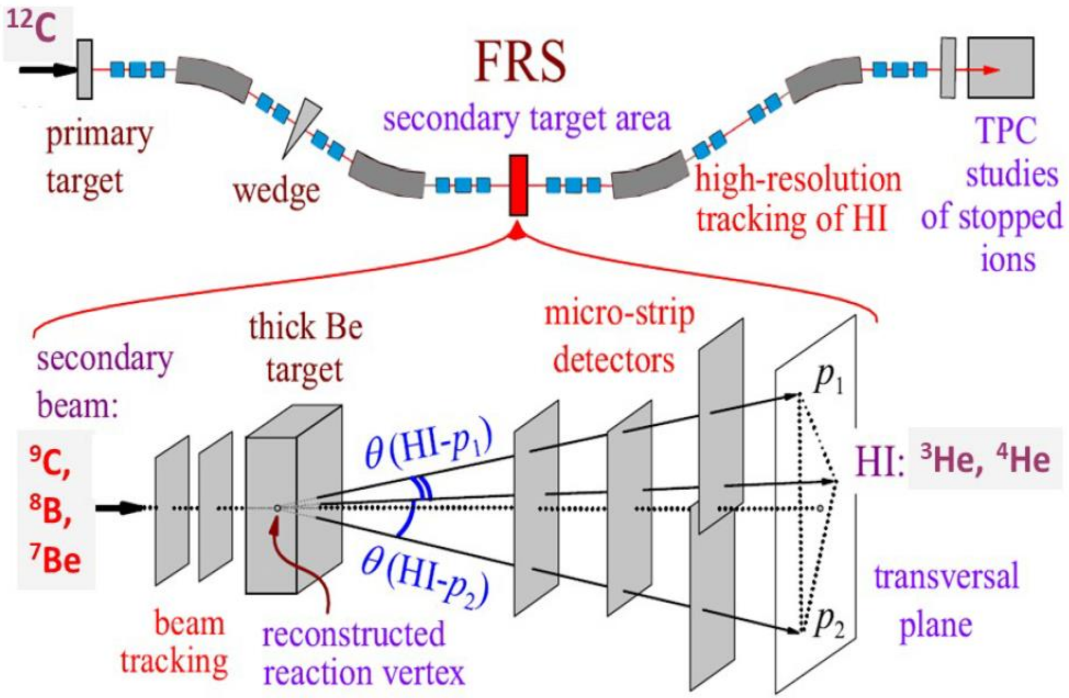
Two pairs of FOOT detectors per arm

Forward detectors for ions

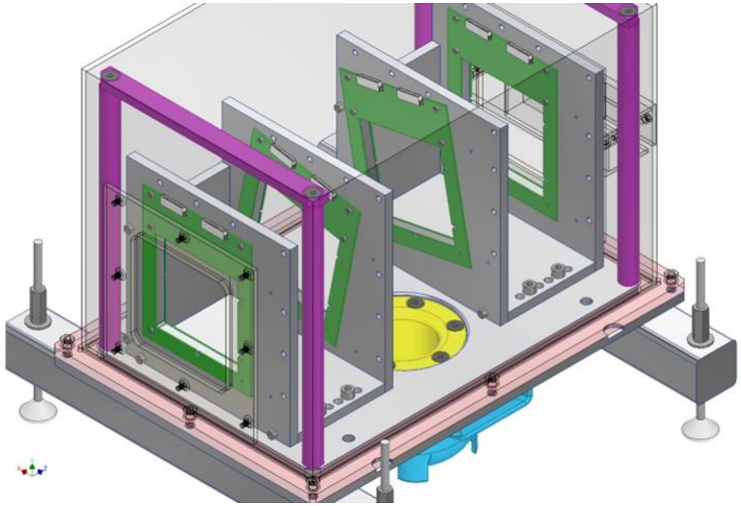




Experiments with in-flight setup at FRS



- in-flight decay method
- EXPERT setup at FRS



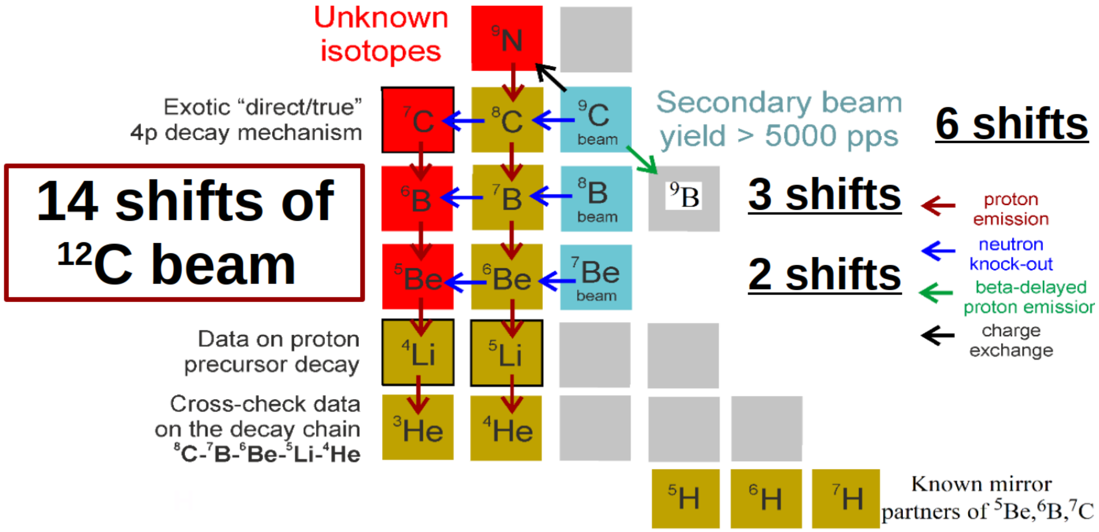
AMS detectors for the first experiments

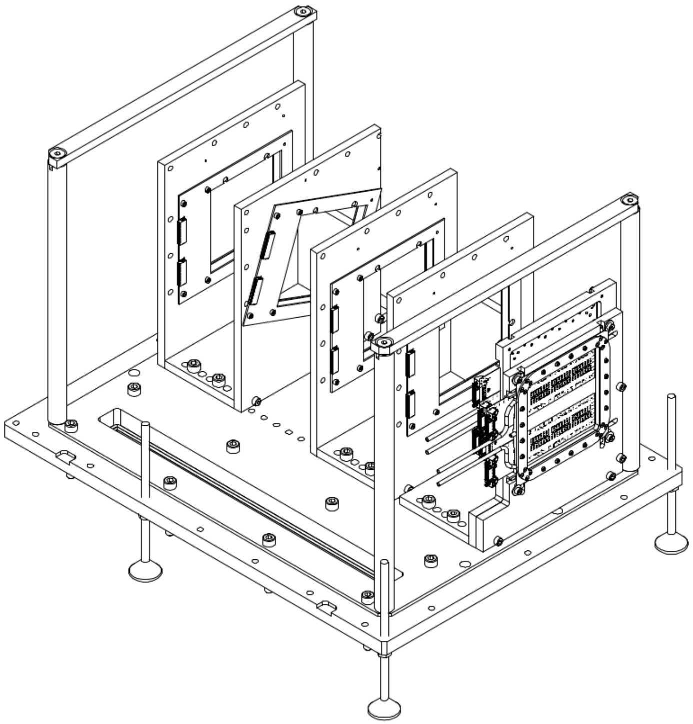
FOOT detectors in 2024 and 2025

Decay of exotic C isotopes at FRS

Isotopes to be studied with secondary beams of ^{9}C, ^{8}B and ^{7}Be produced at FRS

V. Chudoba, D. Kostyleva
May 2025



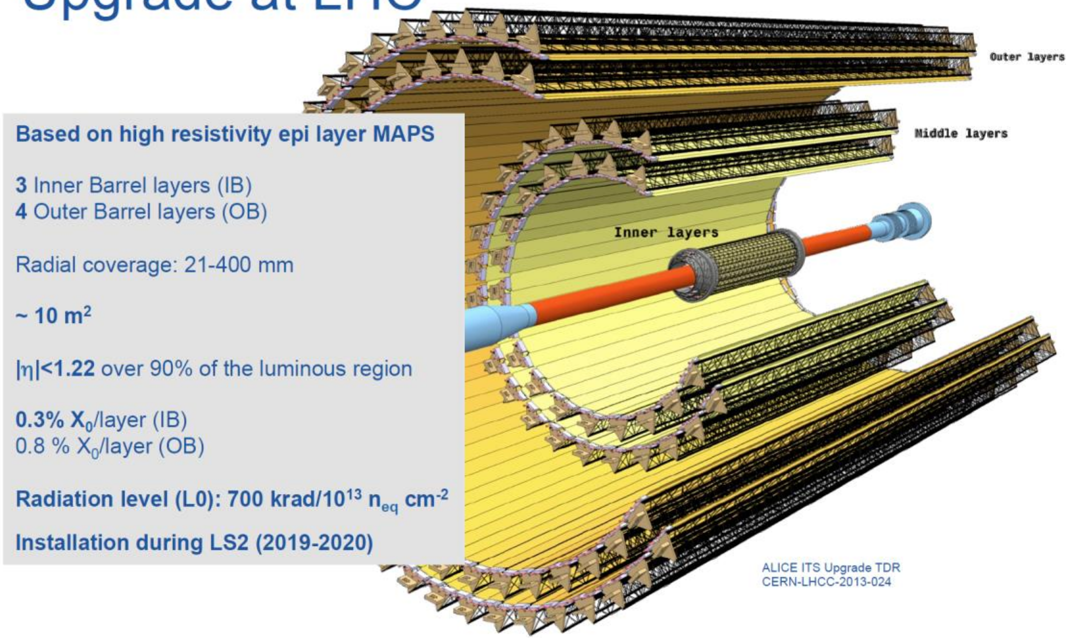


FOOT and **ALPIDE** detectors for protons and ions

Inner Tracker System / ALICE

- CMOS Monolithic Active Pixel Sensor (MAPS) combining the sensor and the readout electronics in one single device
- Thickness of 50 µm or 100 µm (two options)
- Sensor size 15 x 30 mm^2 , 512 x 1024 pixels
- Pixel size 29 x 27 $µm^2$
- TowerJazz 0.18 µm technology
- Power consumption 20 mW/sensor, can work in vacuum with moderate cooling
- Operation in magnetic field up to 0.5 T is possible

ALICE Inner Tracking System Upgrade at LHC

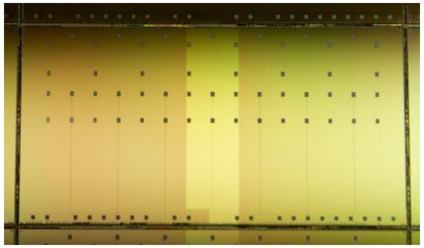


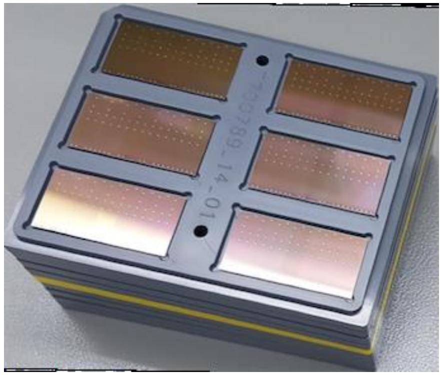
Radiation-hard technology
Dual-use device -> official licence for every user is needed

ALPIDE sensors

- Each pixel cell contains a sensing diode, a front-end amplifier and shaping stage, a discriminator, and a digital section
- Digital readout with priority encoder
- Pixels with no hits are not read out
- Hits recorded independently of trigger and saved in the internal buffer. Trigger starts data transfer from the chip via FPGA to a computer/data storage
- Maximum trigger rate – 100 kHz
- Time resolution ~5 μs
- The detection **efficiency is higher than 99%** for MIPs
- **Spatial resolution - 5 μm** for MIPs
- Noise – around 6 e^-, **threshold – 100 e^-**
- Fake hit rate < 1 Hz per sensor

Implementation needs to be done

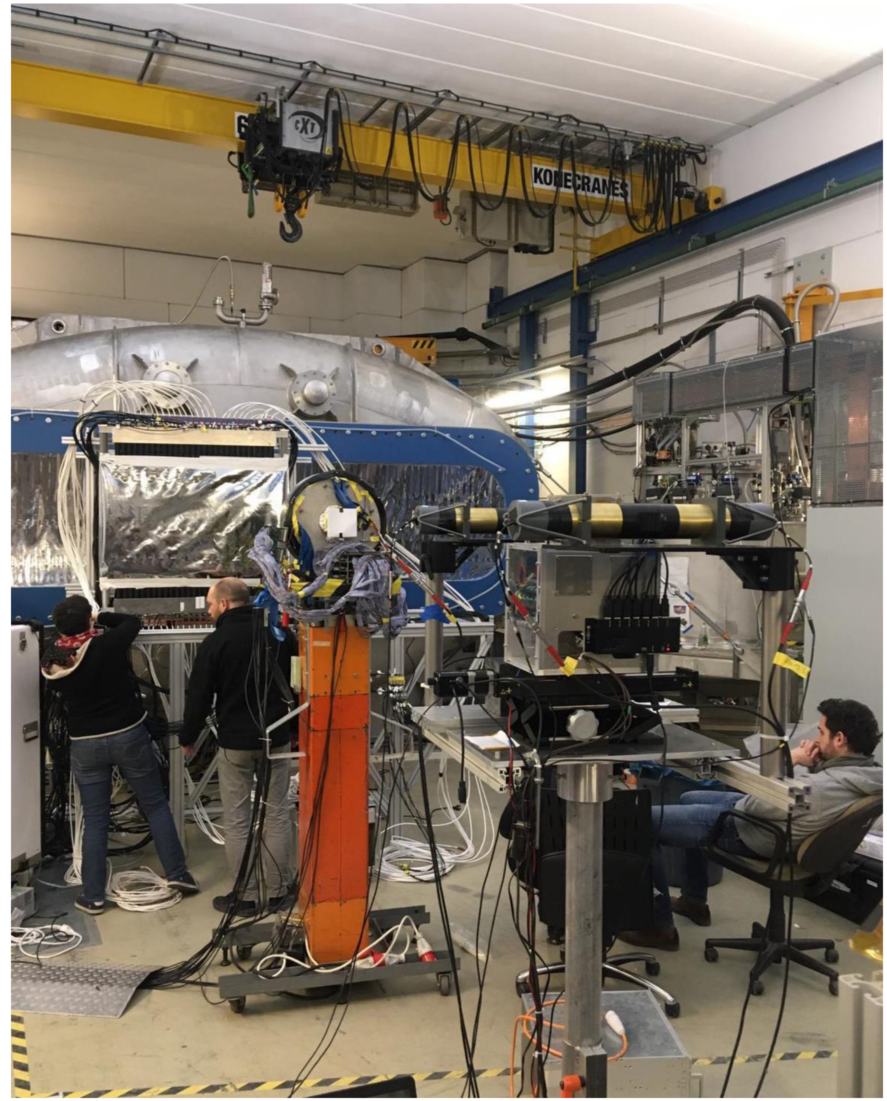




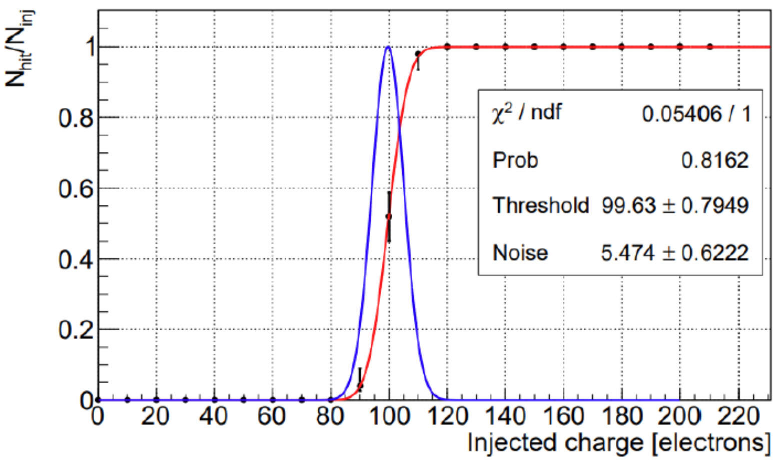
Single carrier card

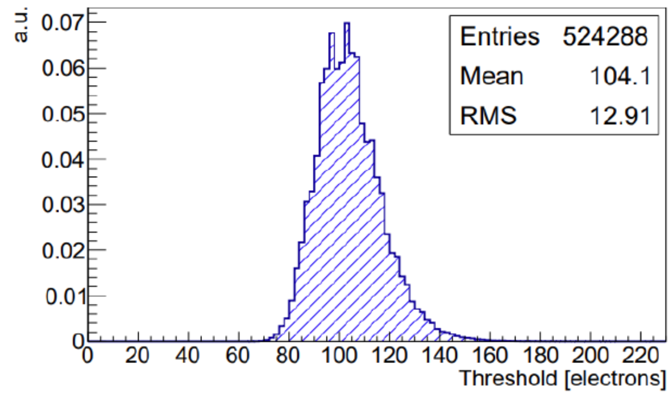
Test of ALPIDE telescope at GSI

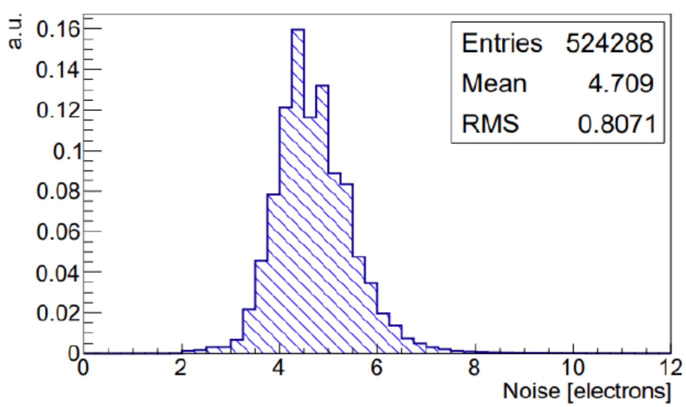
- November 2019, primary Ar beam, variable intensity, 550 MeV/u
- December 2019, secondary Si beam via FRS, 500 MeV/u
- Cluster size/shape study

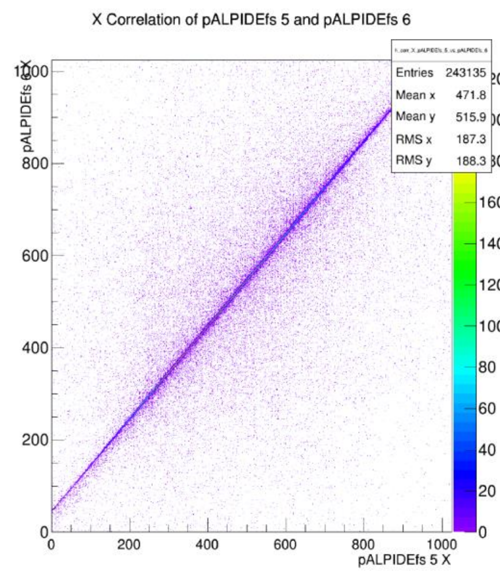


Measurements with ALPIDE





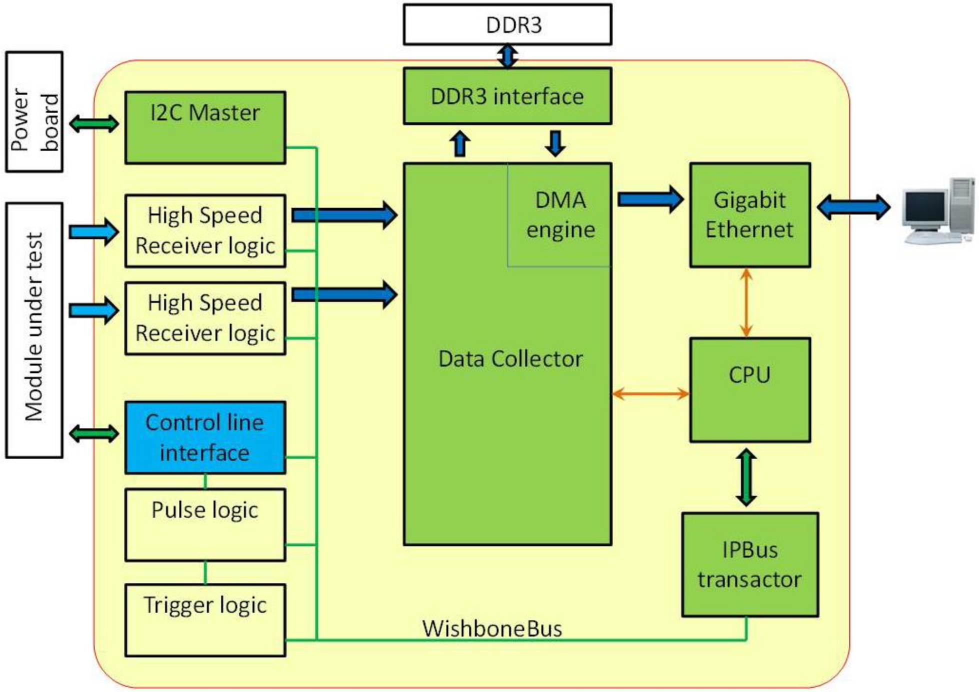


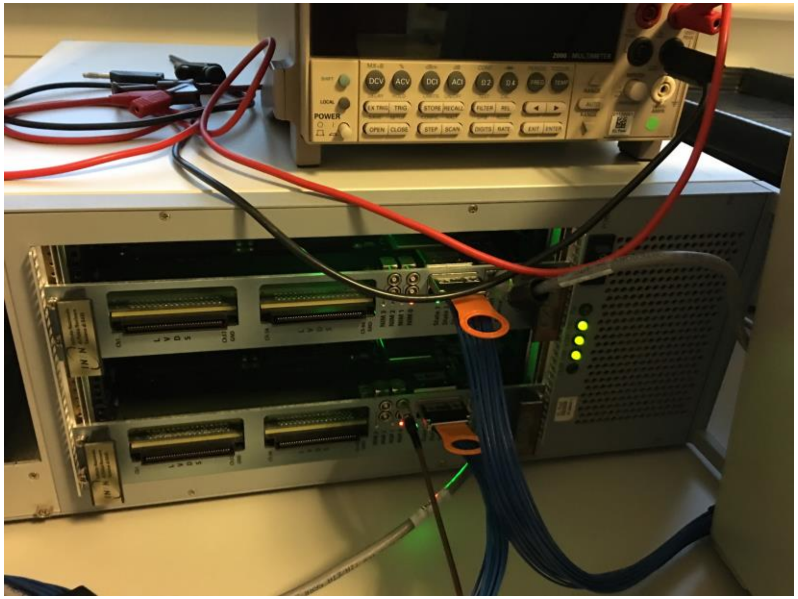


- Runs with the telescope at DESY (e^- beam)
- Very quite detector (noise 5 e^-)!
- Threshold = 130 e^- practically 100% efficiency for MIPs!

B. Blidaru, P. Becht

Readout of the ALPIDE detectors

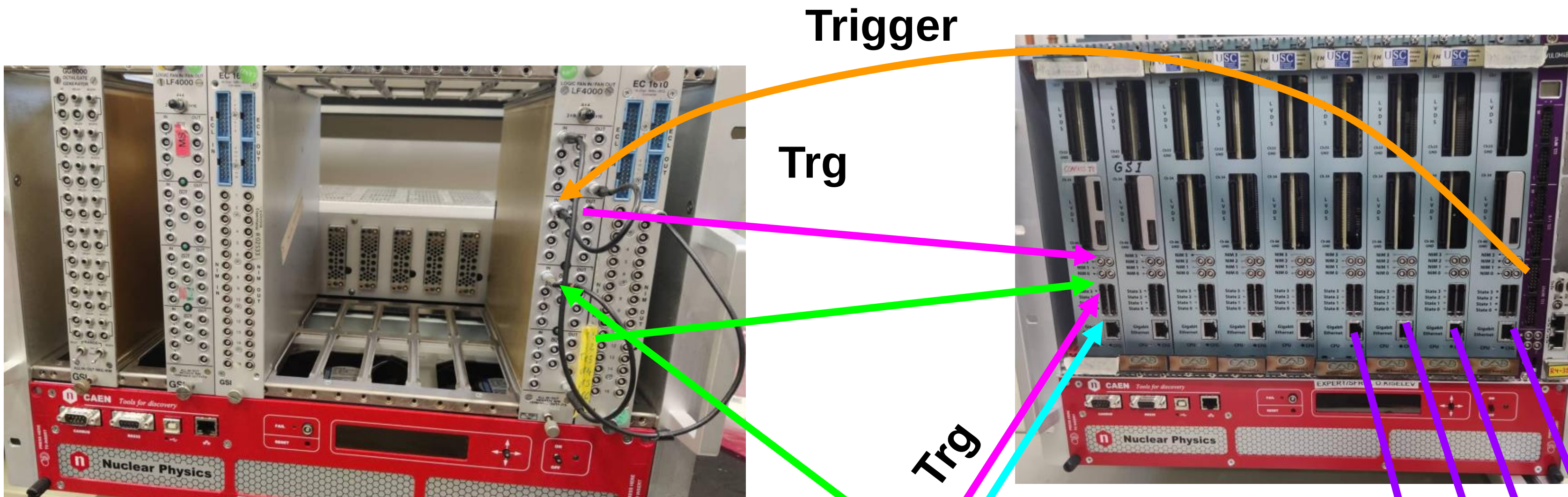


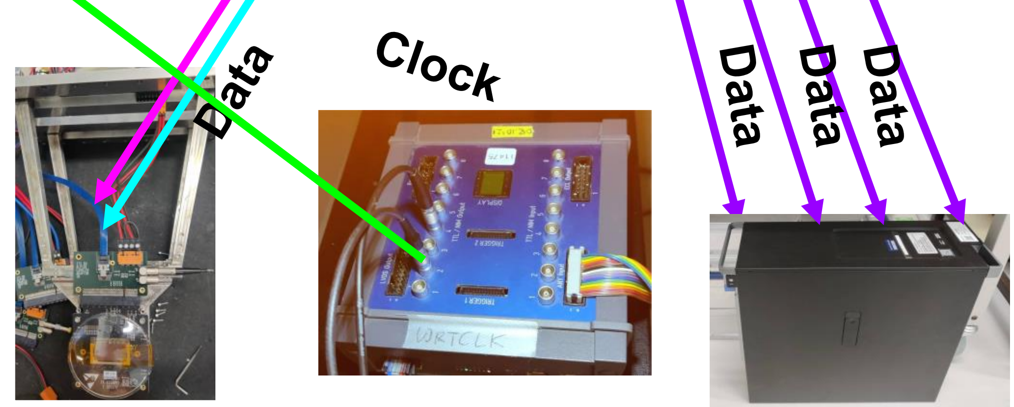


- MOSAIC readout board (INFN Bari)
- FPGA-based, can read up to 9 ALPIDEs
- DAQ for detector test in the lab only, not for the larger setup

Modification, implementation needs to be done

ALPIDE with R3B DAQ

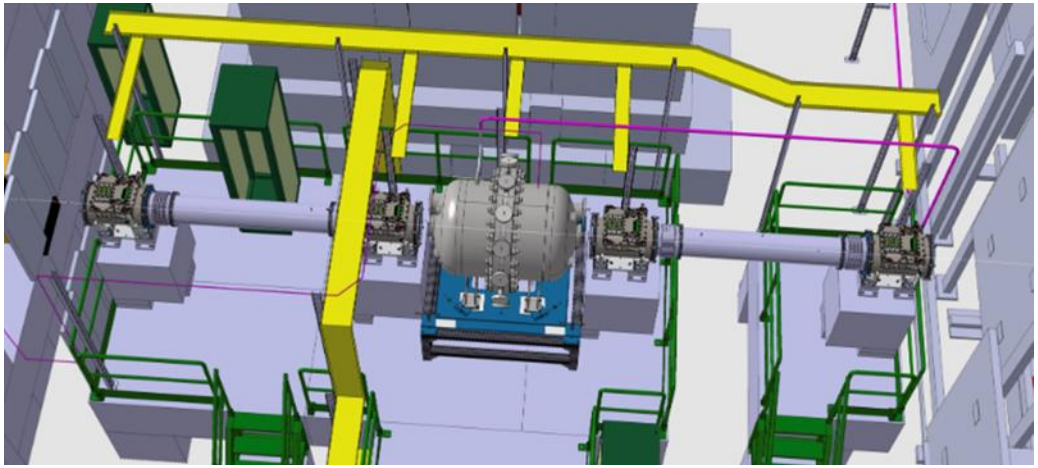


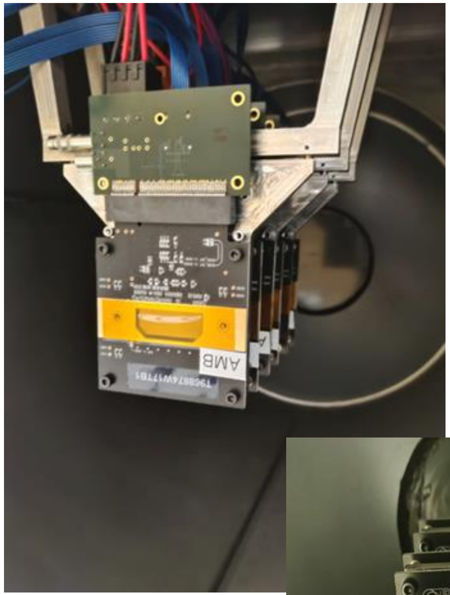


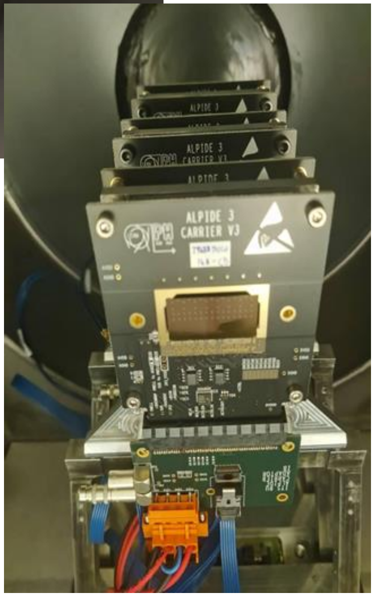
- Rio4 ->VME controller configures pulser
- VULOMB 4B->Generate pulse trigger signal
- EXPLODER->Timestamping WR
- ECL to NIM convertor
- FiFo->Distributes trigger and TS to MOSAICs

Fully different software, partly different firmware

ALPIDE detectors for GSI and AMBER/CERN



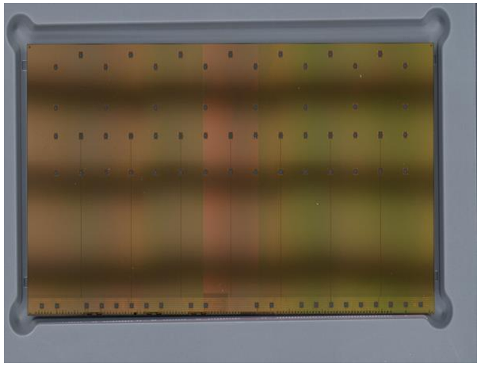




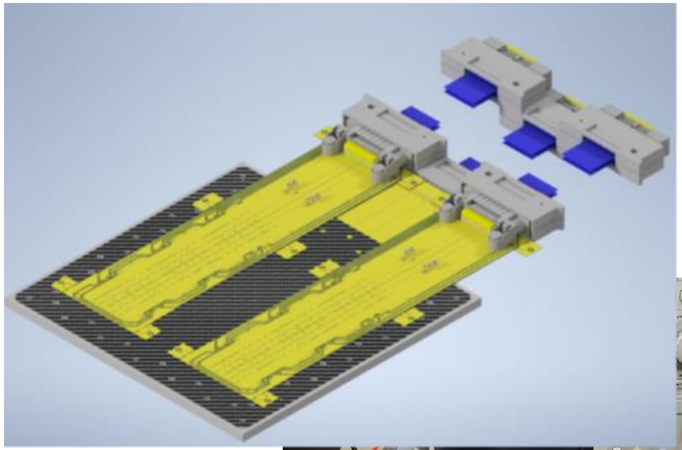
- ➢ Scattering setup for Proton Radius Measurement, muon beam at AMBER / CERN
- ➢ High-resolution ALPIDE-based tracker for incoming and outgoing muons

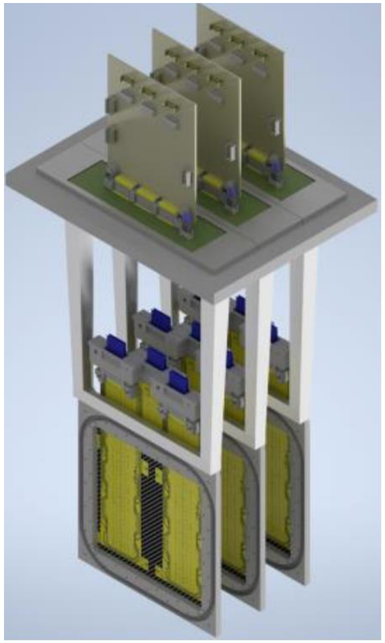
- *Single detector is too small for FRS/SFRS and AMBER beams*
- *Larger stations are needed*
- Cooperation with AMBER due to the common development of the Active Target TPC, continued with the development of tracker

Pixel-based tracking station



From single sensor
to a tracking station





18-sensor station

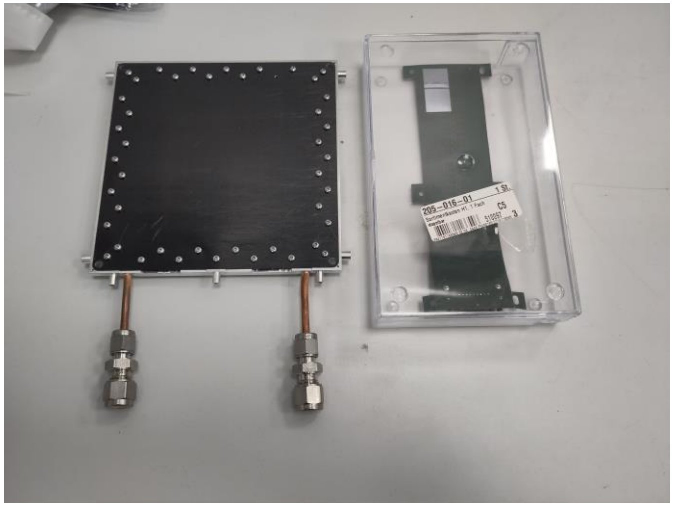
Cooling for work in vacuum

Developed together with AMBER/CERN collaboration

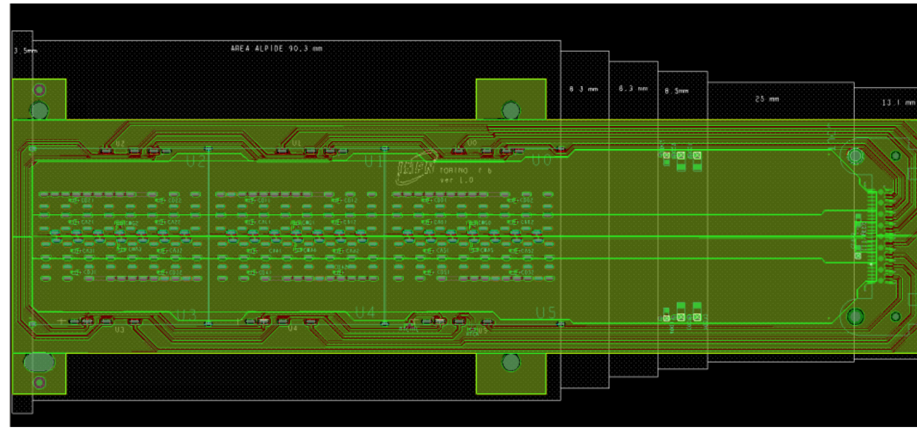
For FRS/SFRS a forward tracker can be ALPIDE-based

Common solution of AMBER, R3B and FRS/SFRS

Components of the tracking station



Cooling/holding frame with carbon fiber plate and the flex



6-detector flex; design and a real unit

Currently the detectors are mounted at Daresbury lab, UK using a coordinate measuring machine Mytutoyo

Bonded at GSI detector lab

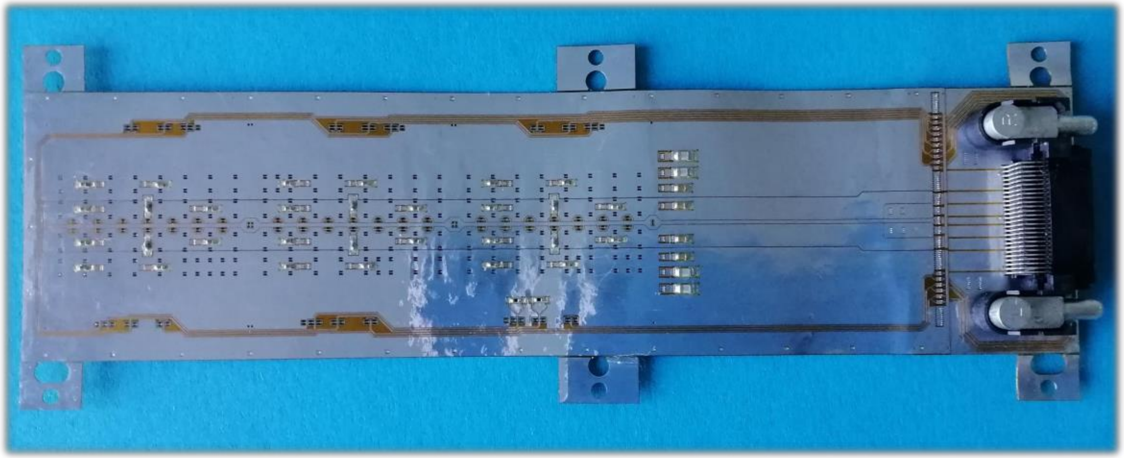
Test setup at GSI

Produced at CERN, Al-based, 110 µm thick

Components of the tracking station

First ALPIDE detectors (2 wafers) for mounting on the flexes at GSI

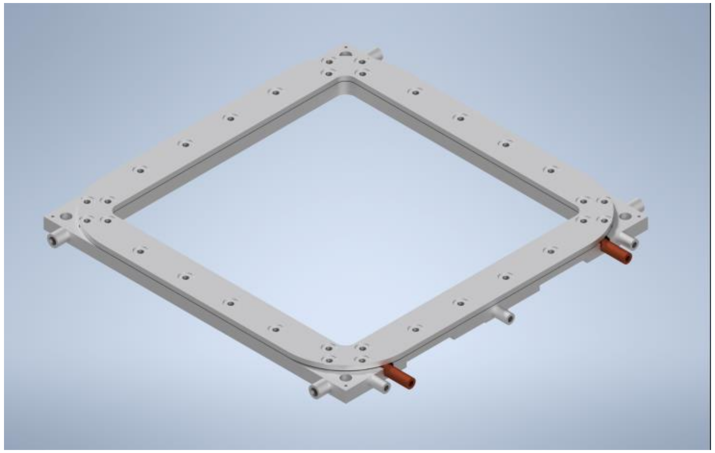
30% gold grade, 30% silver grade, 5% bronze grade

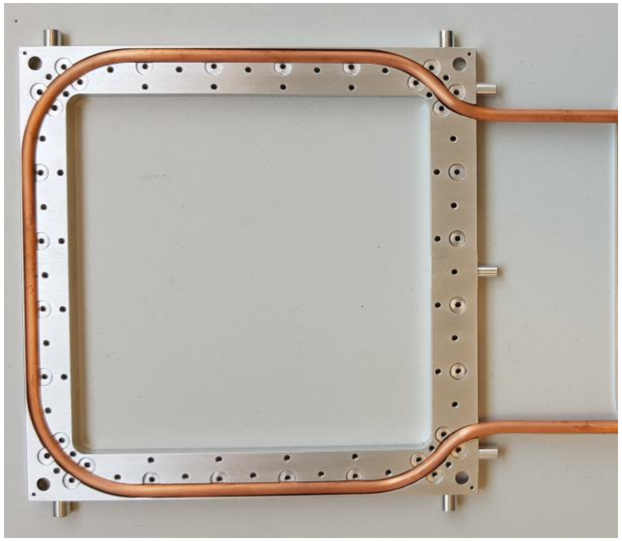


6 Al-based flex boards are made by LTU

Another production possibility at LTU, Kharkov, Ukraine

Cooling/holding frame for the ALPIDEs



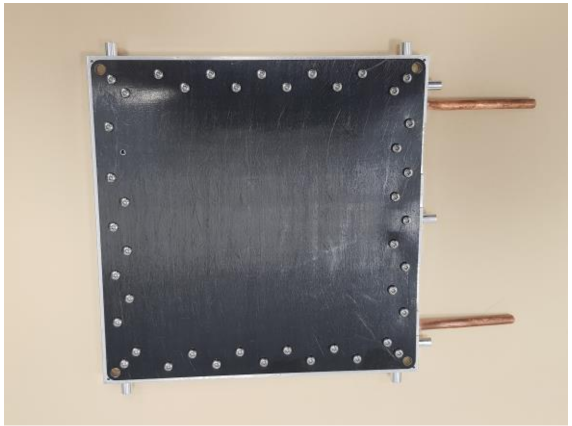


Al holding/cooling frame with a Cu tube inside,
10 µm precise construction, positions for the fixation inside larger setup

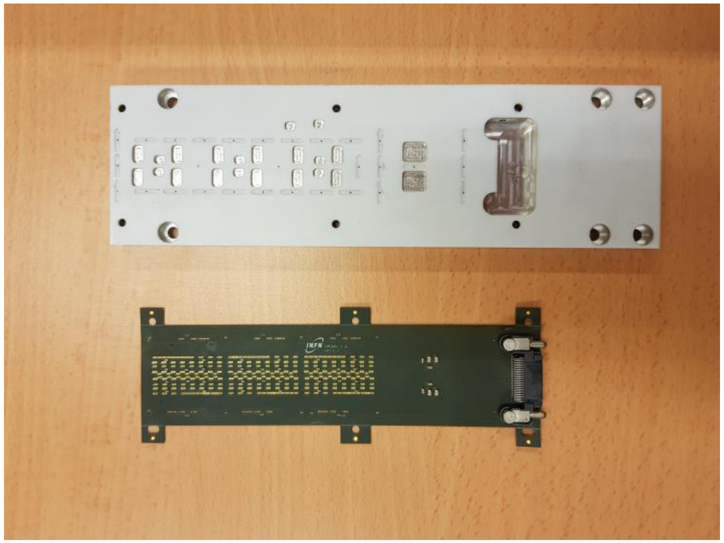
Frames are produced at GSI

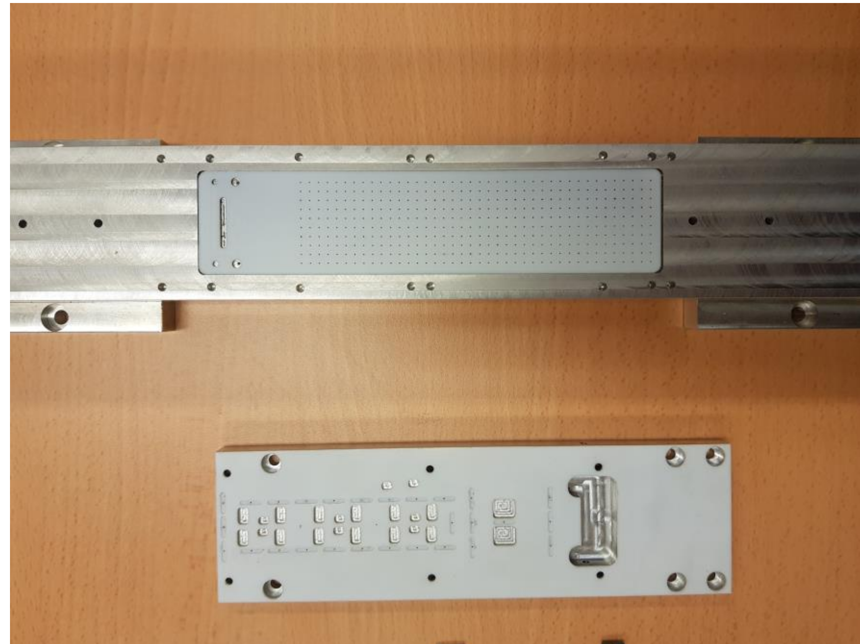
Carbon fiber plate for holding the detectors, very high thermal conductivity, 240 µm thick

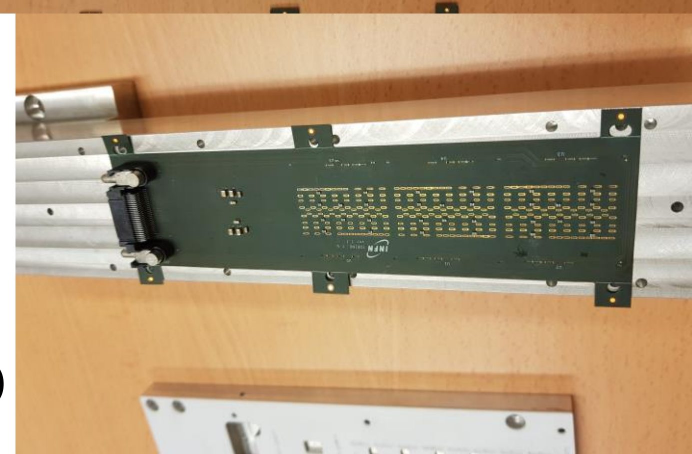
Carbon plates produced at CERN



Tools for assembling the detectors on the flex boards





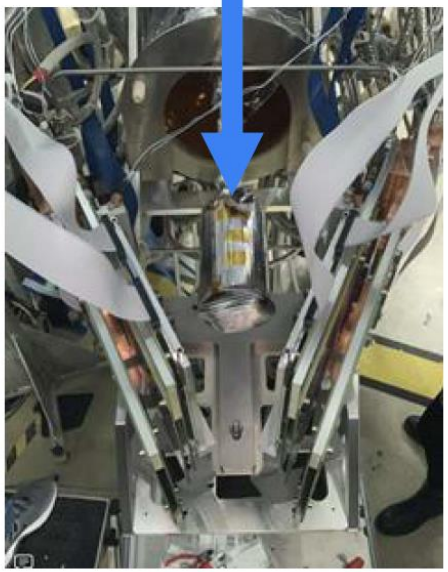


Tool for vacuum fixation of the flex for gluing

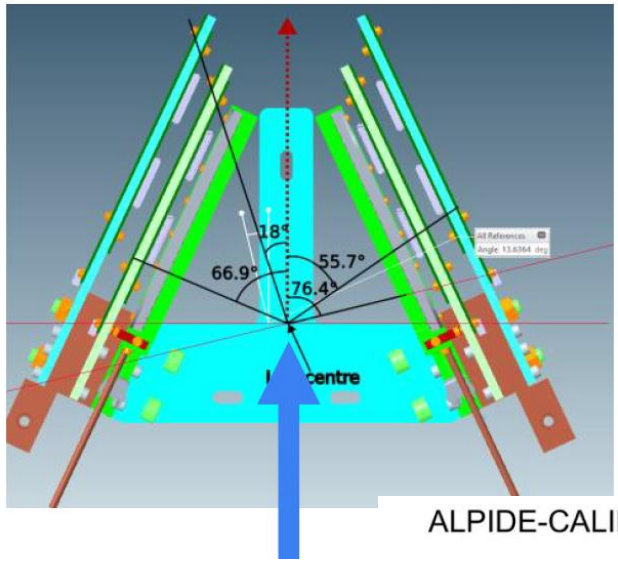
Tool for the vacuum fixation of 6 detectors before gluing

Positioning with a 10-20 µm precision (calibrated pins)

FOOT – ALPIDE combined R3B tracker



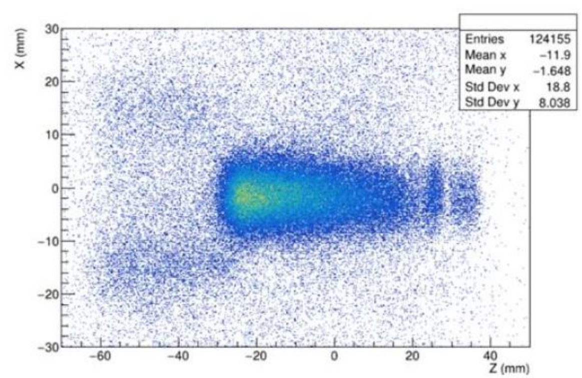
S091 experiment

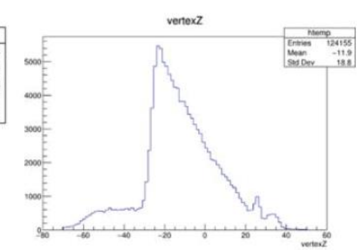


1st layers – ALPIDE stations
2nd and 3rd layers – FOOT detectors

ALPIDE-CALIFA vertex reconstruction

- Substantial improvement of vertex reconstruction
- Detailed structure of the liH2 target visible





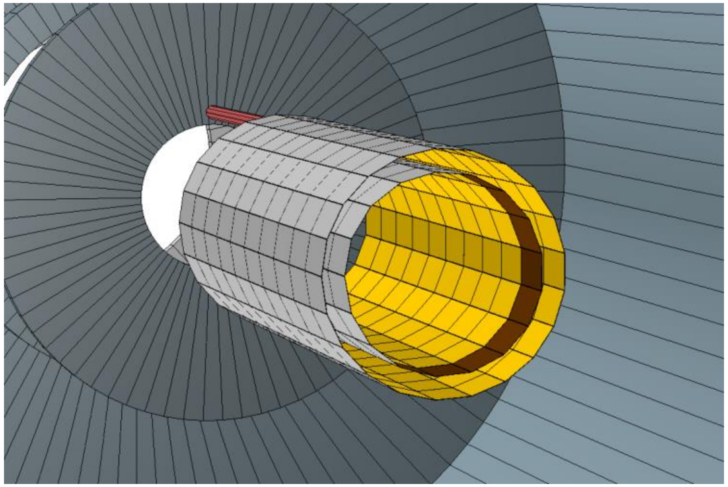
Reduction in downstream reactions due to lack of forward angle coverage

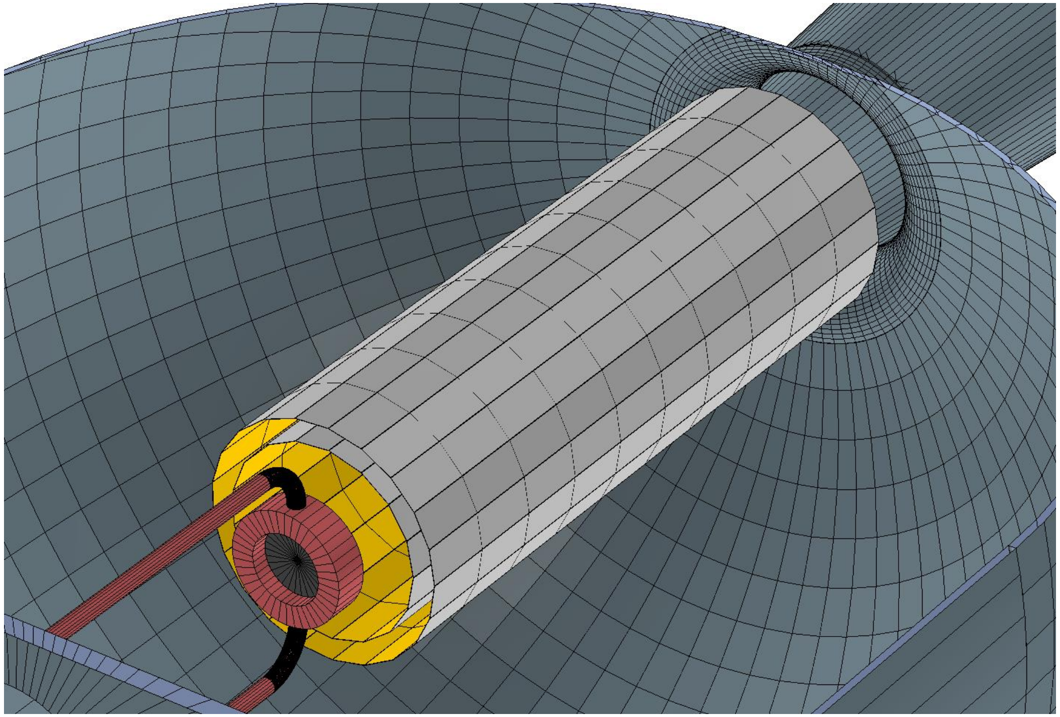
Matt Whitehead

R3B Target Recoil Tracker Stage 2

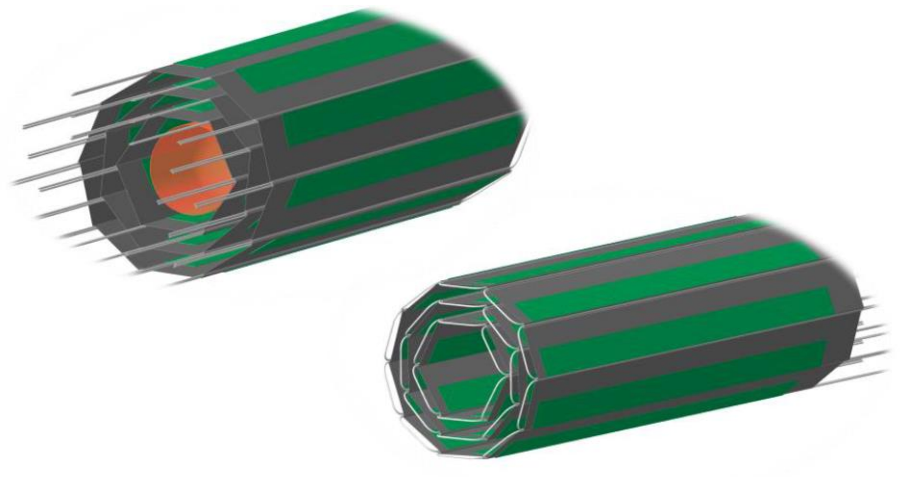
Two barrels made of 38 multi-Flex boards with 363 ALPIDE sensors in total

- Inner barrel
  17 flex boards
  9 sensors per multi-Flex
- Outer barrel
  21 flex boards
  10 sensors per flex





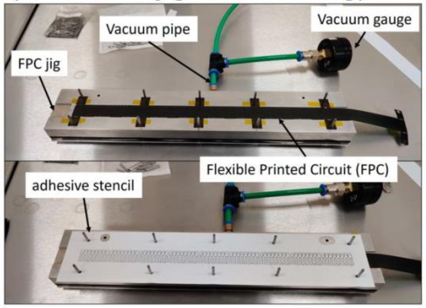
R3B Target Recoil Tracker Stage 2



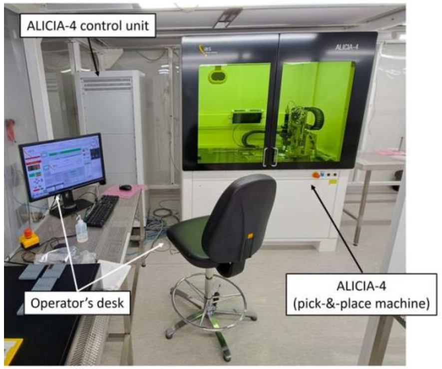
Dave Seddon and Enrique Casarejos

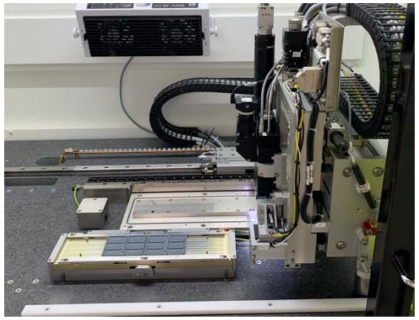
ALICIA installed and operational
3 people have been trained to operate
Reproducible results within few um precision.

Prototyping jigs
(while final jigs are arriving)



stencil





10 FPCs Stage 2 prototypes produced
(Cu based)

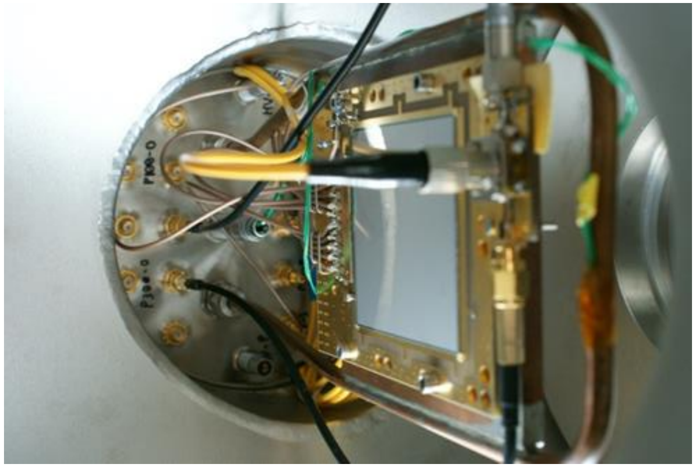
S. Paschalis, York, UK

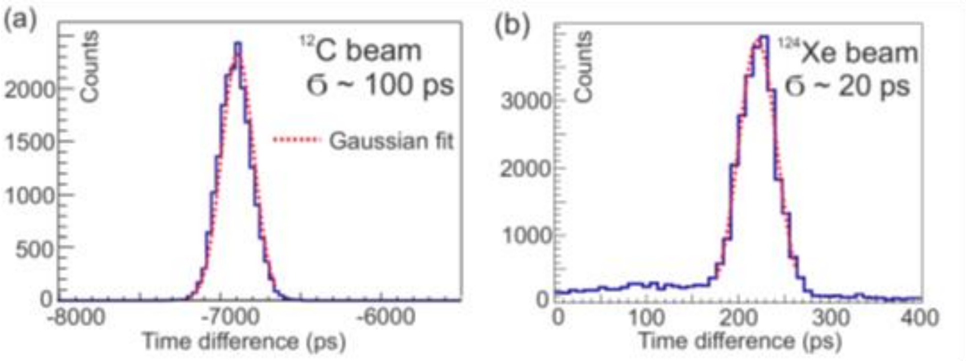
TOF Si planar detectors

Measurement of TOF with large-size SSD

1. Thickness --------300 um
2. Strip pitch ------1 mm
3. Inter-strip gap --- 50 um

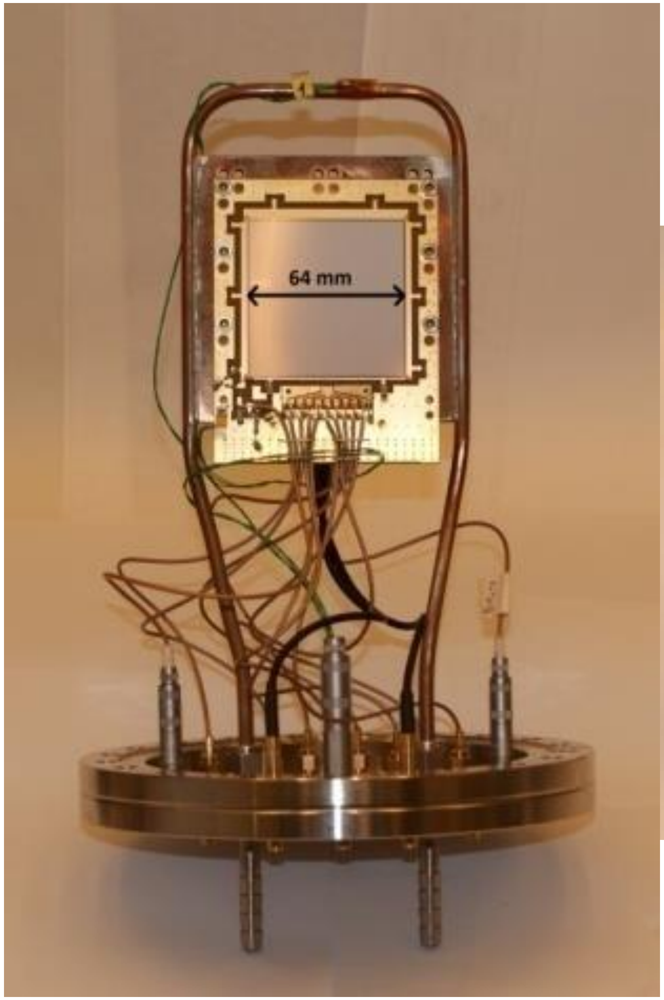
•Signals processed by front-end (PADI-X ASICs) and FPGA TDC –TAMEX2 boards (resolution 7 ps)
•Rate capability ~1 MHz/ch





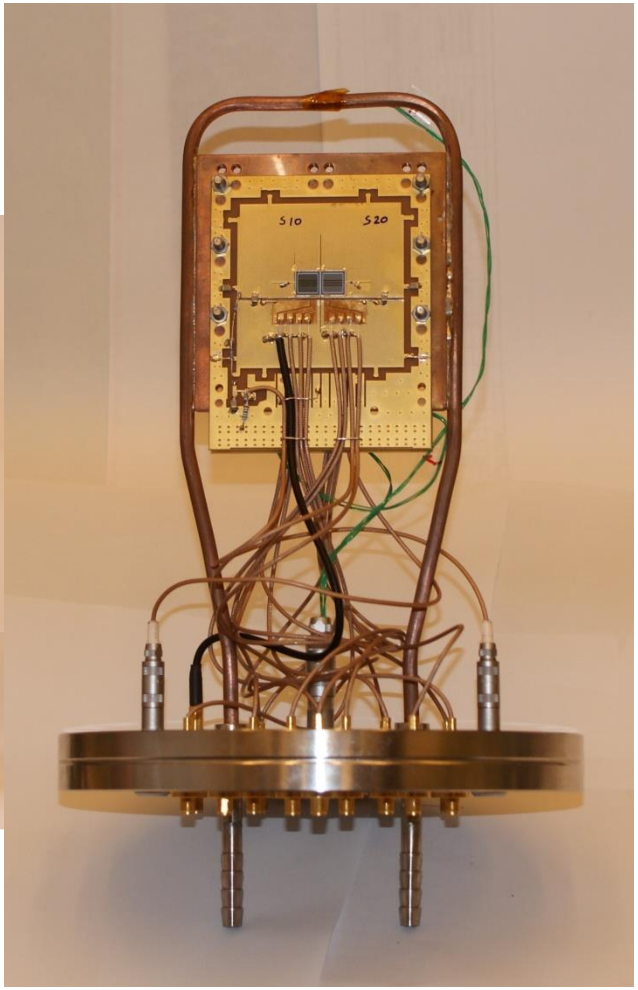
Rare example of custom Si strip development

Mounted detectors



Big SSD

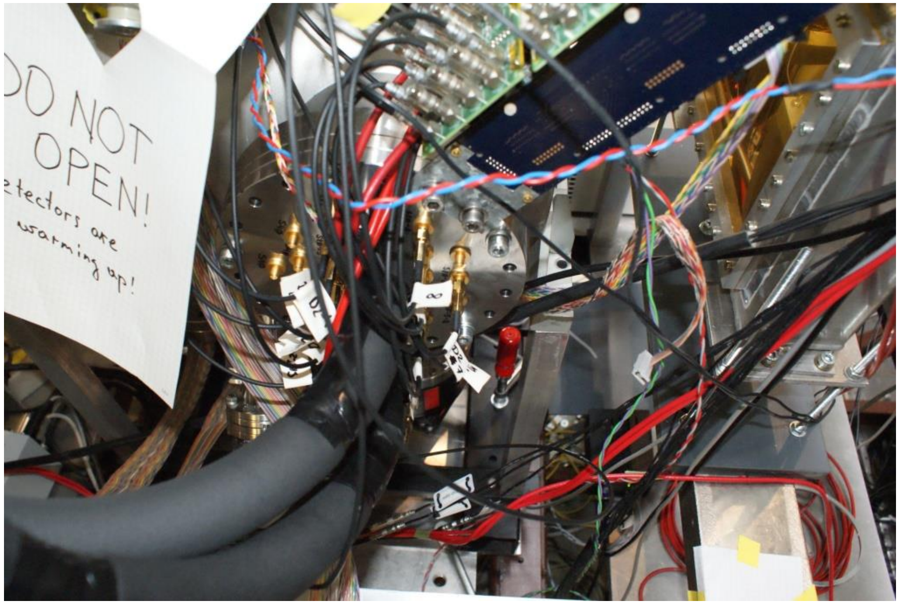
External part of the flange



Small SSDs – S10, S20

DAQ for TOF tests

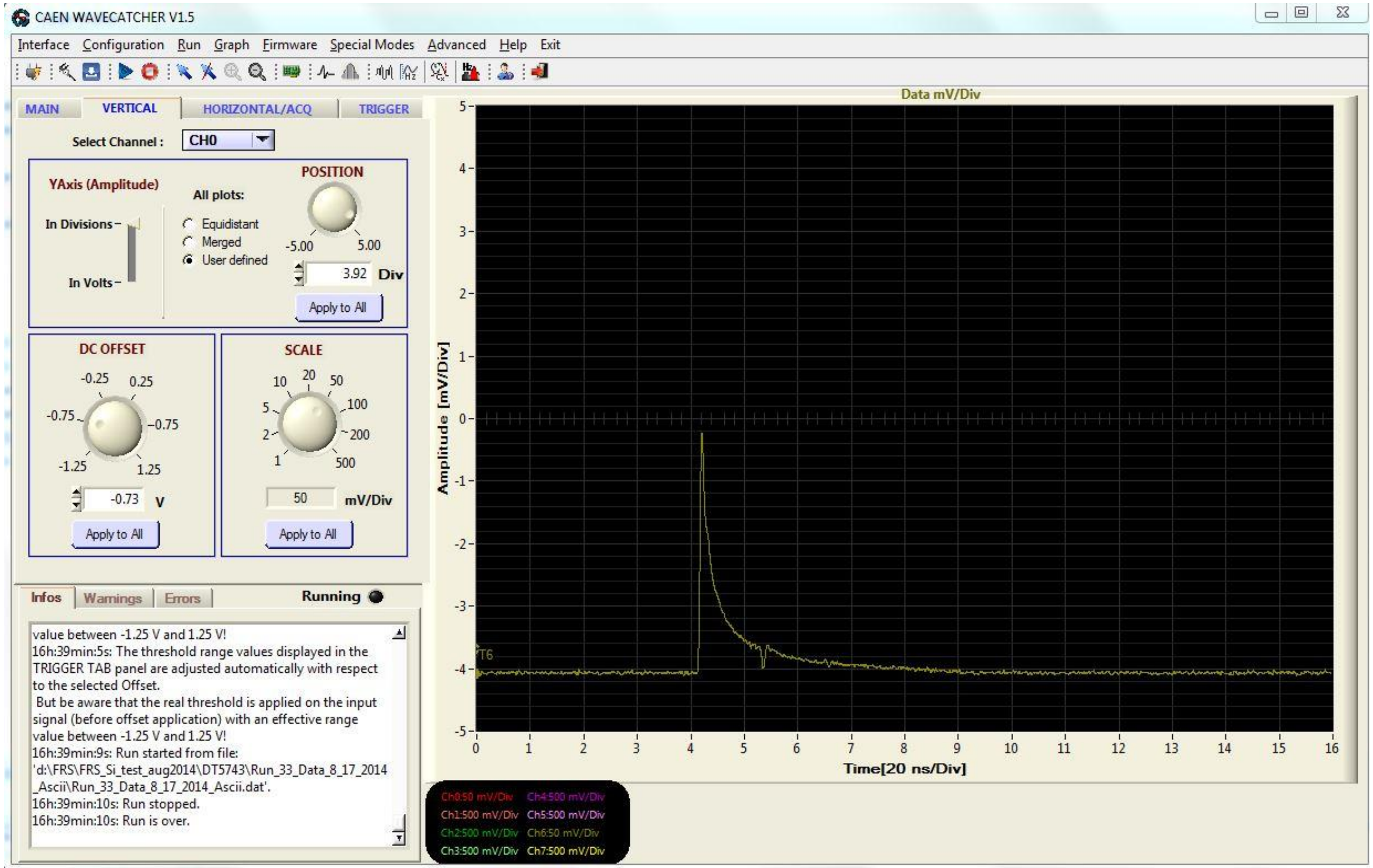
- CAEN FADC DT5743. Sampling frequency up to 3.2 GS/s
- PADI preamplifier/discriminator + VFTX2 TDC
- CAEN FADC DT5742. Sampling frequency up to 5 GS/s



Signal processing for TOF

FADC DT5743, sampling frequency up to 3.2 GS/s

- The digitized amplitudes of the signals are interpolated with splines.
- CFD method for walk correction.



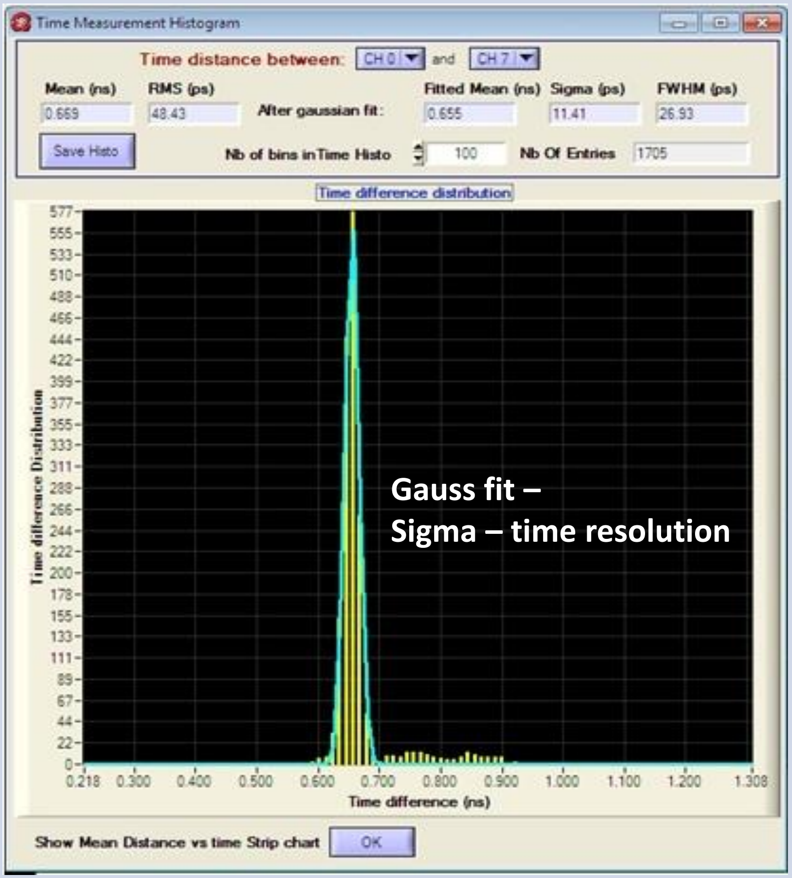
Signal from Si strip detector itself

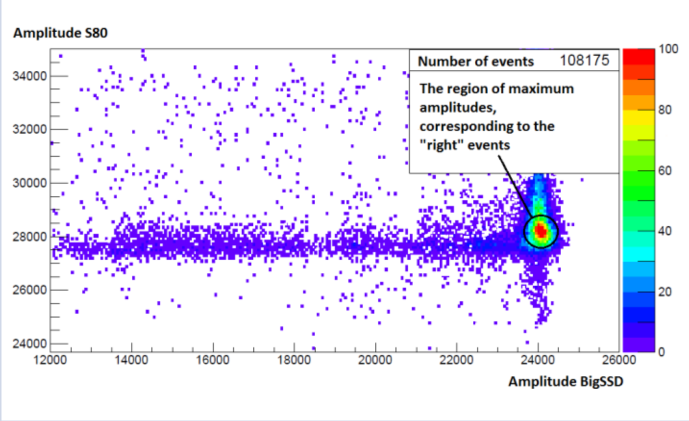
No electronics

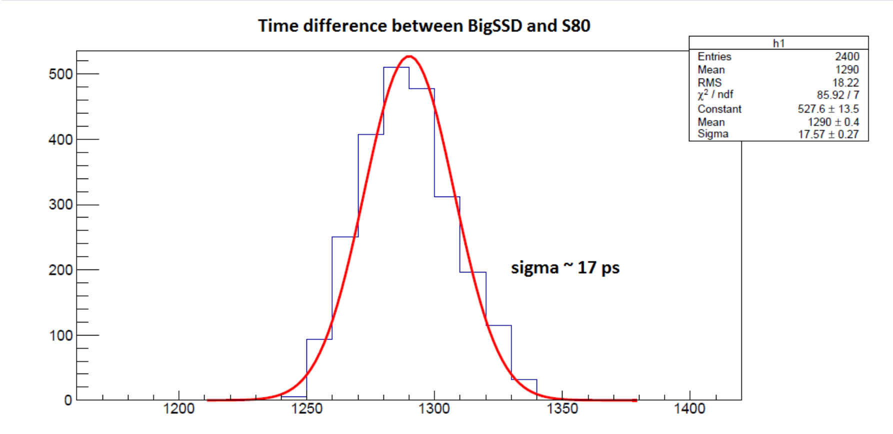
TOF resolution

DT5743	PADI + VFTX

CAEN WaveCatcher

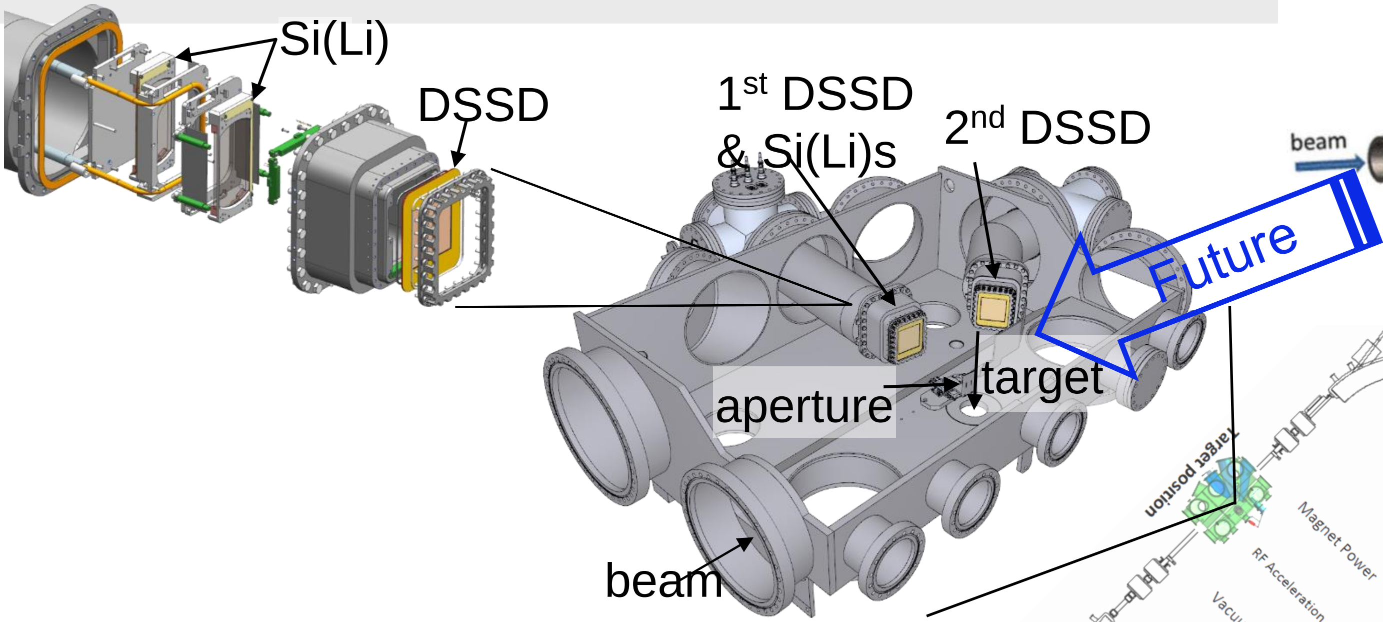


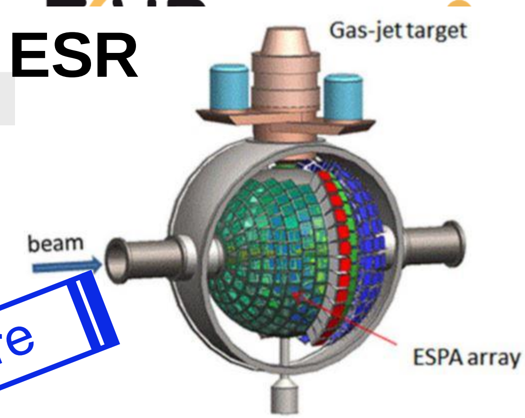


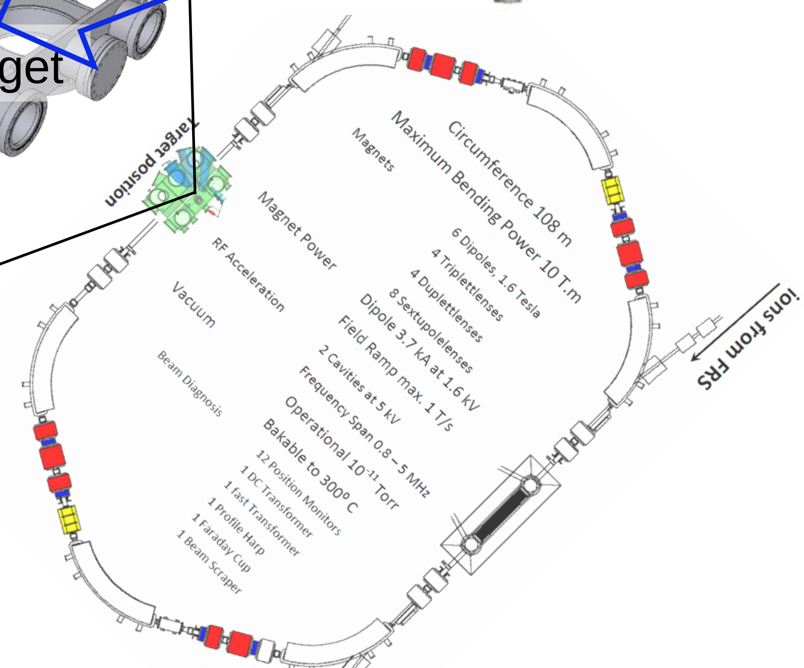


Internal Target Experiment

Experimental Setup for Internal Target at ESR







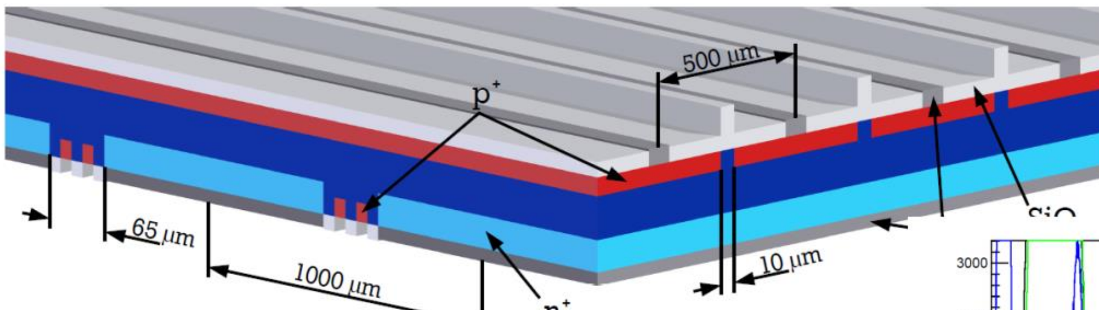
- **DSSD**: 128×64 strips, (6×6) cm², 285 µm thick, **dead layer of only 40 nm (extremely low energy threshold)**
- **Si(Li)**: 8 pads, (8×4) cm², 6.5 mm thick
- **DSSDs as active vacuum barrier/window**
- **UHV inside the chamber – backable detectors, cables**

Successful experiment in 2012, several high-level publications

Another rare example of custom Si strip detector development

DSSD for EXL experiment at ESR

PTI design of full size DSSD (64 x 64 mm²), thin entrance window for low energy cut-off



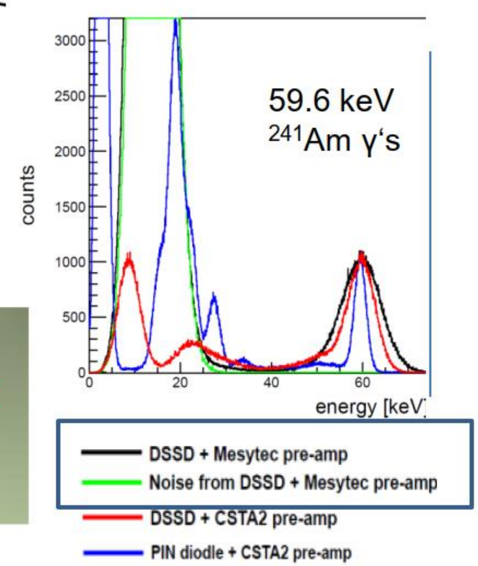
DSSD:

Active area: 64 x 64 mm ^{2}, Thickness: 285 µm
Pitch size: 0.5 mm on p-side, 1 mm on n-side

Dead-layer (measured):

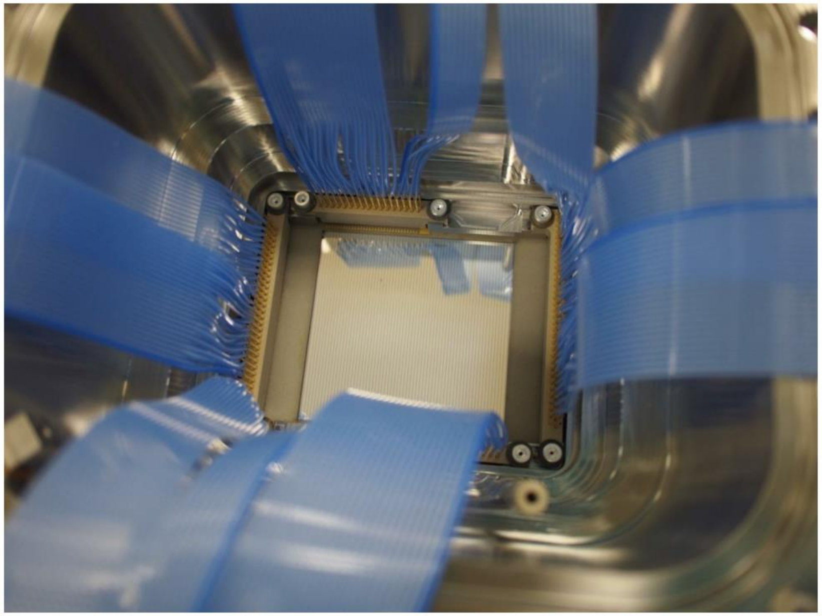
- 0.06 - 0.08 µm (SiEq) on p-side
  3.6 µm on n-side
- Energy resolution: ≤ 15 keV fwhm

Low energy cut-off by dead-layer is very low:
2 -3 keV for alphas
1.5 keV for protons



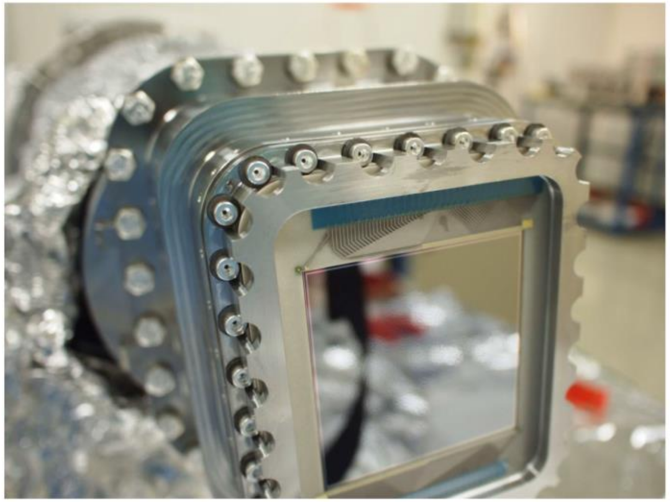
Low-energy limit defined by electronic noise to > 20 keV

DSSD in UHV

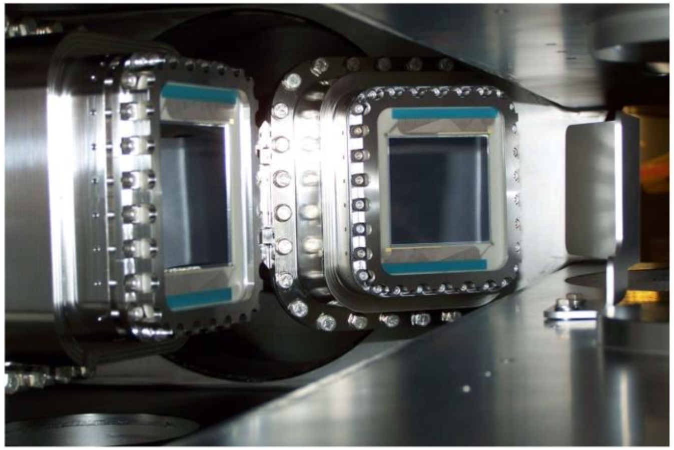


DSSD1 with spring-pin PEEK connector and PTFE ribbon cables

- Detectors acted as vacuum window
- Backed during heating of ESR
- Measured dE and X, Y coordinates



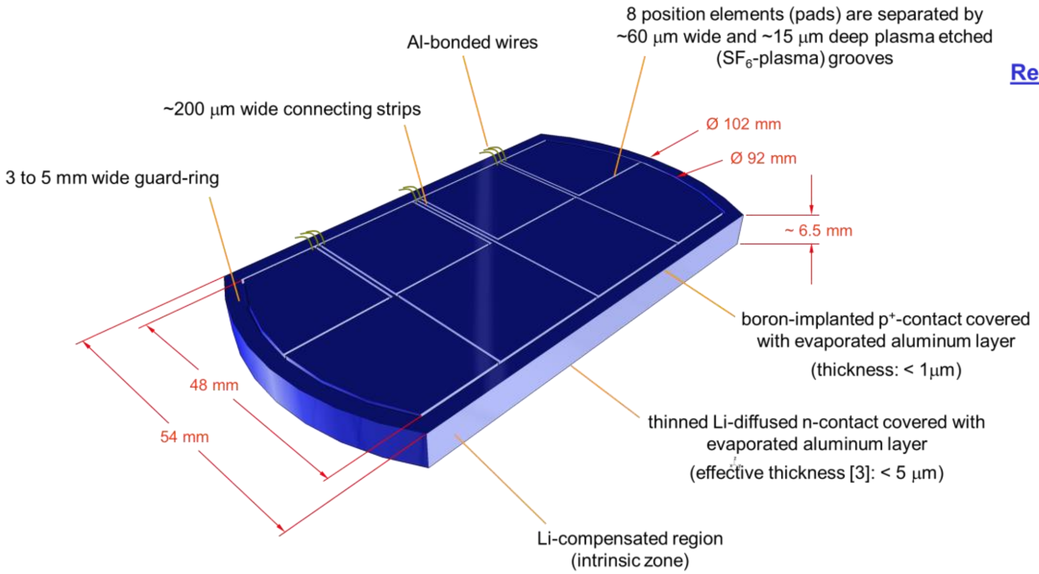
UHV front side of DSSD1



Front-sides of DSSD1 & DSSD2 tubes inside scattering chamber

Si(Li) detectors at EXL setup at ESR

Schematic view of the Si(Li) transmission detector



Results of the first laboratory measurements

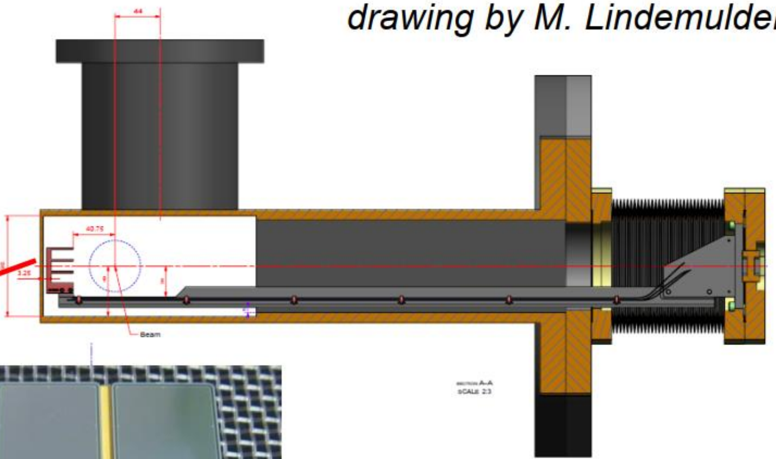
EXL-1 operating bias: +700 V	298 K	283 K	275 K
• reverse current (total)	20 μA	6.0 μA	3.1 μA
• reverse current per pad	110-200 nA	30-60 nA	15-31 nA
• resistance pad - neighbourhood	> 1 MΩ	> 1 MΩ	> 1 MΩ
• energy resolution [FWHM] per pad for 5.8 MeV α-particles	26-41 keV	25-30 keV	23-25 keV
• energy resolution [FWHM] per pad for pulser line	15-29 keV	13-20 keV	11-13 keV

- Detectors used for full energy measurement of protons and alphas
- Actively cooled down to -15° C during heating of ESR and the whole experiment
- Developed and produced at IKP, FZJ

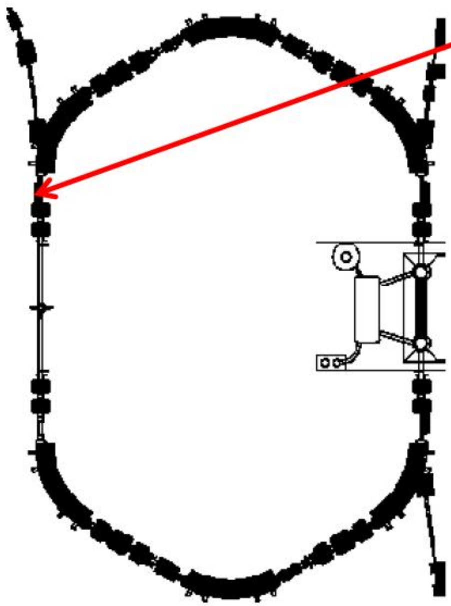
Detectors for heavy ions at ESR

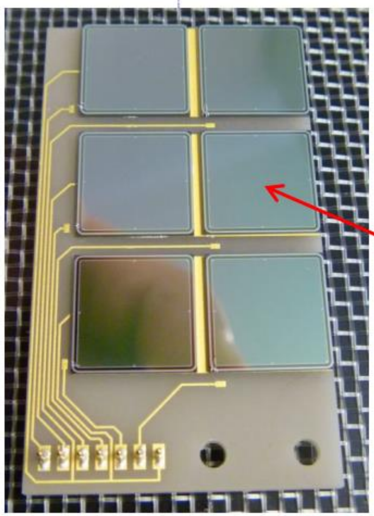
Down-stream Silicon PIN diode array

- In-ring detector for coincidence measurement of beam-like particles before the first dipole
- Movable arm inside UHV



drawing by M. Lindemulder, KVI





Pocket and PIN diode arm built @ KVI

6 PIN diodes 1x1 cm^2,
500 µm thick
(Siemens SFH871)

- mounted on AlN PCB
- bakeable to 250 ^{0}C
- Silver-filled, conductive glue H22 EPO-TEK®

UHV Test for operation in ESR UHV environment passed

M. Mutterer, GSI

Conclusions

- Silicon strip and pixel detectors find many applications in nuclear and particle physics
- Examples of EXL, FRS, R3B and AMBER clearly demonstrate it
- These detectors are many-fold usable, mainly for tracking but also energy measurement, and even TOF
- Silicon detector development is clearly driven by large collaborations, smaller ones normally make adaptations for their needs
- Last years, application of MAPS pixel detectors (developed for particle physics) seems to be a very promising solution for nuclear physics experiments