The Silicon Tracking System of the **CBM** experiment at FAIR

Maksym Teklishyn[1,2]
for the CBM Collaboration

[1]Facility for Antiproton and Ion Research (Darmstadt, Germany),
[2]Kyiv Institute for Nuclear Research (Ukraine)

Strangeness in Quark Matter — July 14, 2017, Utrecht

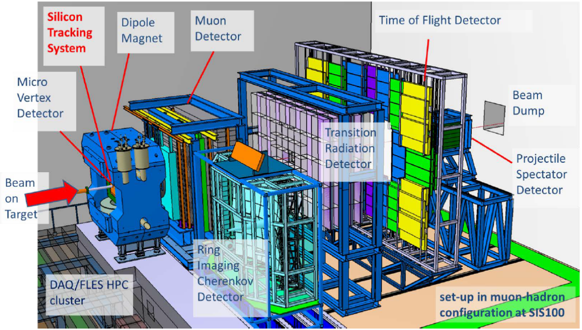
CBM experiment at FAIR

Physics aim: QCD phase diagram
at high net baryon densities and moderate temperatures

- Starting with SIS100 energies:
  $2 - 11\,\mathrm{GeV}A$ ($\sqrt{s_{NN}} = 2.7 - 4.9\,\mathrm{GeV}$)

Observables:

- Hadrons, electrons, muons, photons
- Particle yields and multi-differential cross-sections
- Rare diagnostic probes: strange mesons, light vector mesons (ρ, ω, ϕ), charm production



Recent publication: Challenges in QCD matter physics - The scientific programme of the CBM experiment at FAIR; arXiv:1607.01487v2 [nucl-ex] 24 Nov 2016

Silicon Tracking System

- Silicon Tracking System (STS) is a core CBM[1] detector
- 8 tracking stations
  - 30 cm downstream the target
  - about $3.0 \times 1.0 \times 1.4\,\mathrm{m}^3$ large
  - material budget $0.3 - 1.0\%\,X_0$ per station
- Operation conditions:
  - inside $1\,\mathrm{Tm}$ dipole magnet
  - thermal enclosure, operation temperature $-7^\circ\mathrm{C}$
  - lifetime dose in the innermost regions $\simeq 1 \times 10^{14}\,{}_{1\,\mathrm{MeV}\,\mathrm{n_{eq}}}$
- Expected performance:
  - single-point resolution $\Delta x \leqslant 20\,\mu\mathrm{m}$
  - hit reconstruction efficiency $\geqslant 98\%$
  - momentum resolution $\Delta p/p \approx 1.5\%$

[1] Claudia Höhne, *CBM@FAIR* (Saturday 11:25)

Technical challenges

Requirements from the physics program:

- Studies of the rare probes
  - low cross-sections $\longrightarrow$ high interaction rates (up to $10\,\mathrm{MHz}$)
- Low momentum particles ($> 0.5\,\mathrm{GeV}/c$)
  - multiple scattering is important

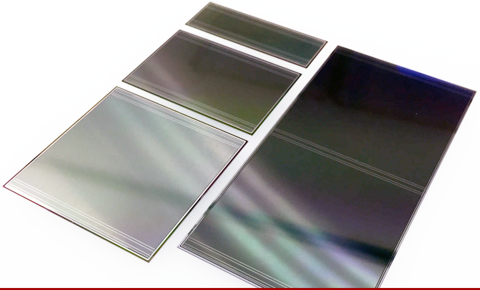
Consequences for the detector:

- Fast self-triggering r/o electronics, no hardware trigger
- Double-sided double-metal thin silicon sensors
  - all strips read-out from one edge
  - smaller amount of material
- Read-out via the long micro-cables:
  - variable length from $11\,\mathrm{cm}$ to $51\,\mathrm{cm}$
  - electronics outside the acceptance: material$\searrow$, rad. dose$\searrow$

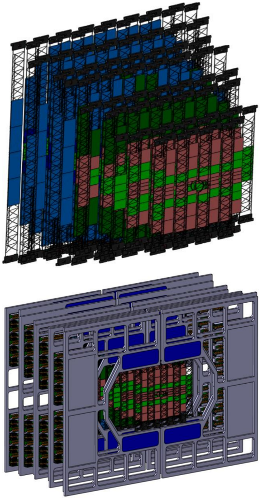
Fast, large, precise and light solid-state detector

Silicon microstrip sensors

- Double sided n-type silicon sensors (XY positioning)
  - n-side 1024 straight strips
  - p-side 1024 strips turned by 7.5° to the edge
    + second metallisation layer to interconnect short strips
- Various form factors (≈ 300 of each $\geqslant 42\,\mathrm{mm}$):
  - $22 \times 62\,\mathrm{mm}^2$, $42 \times 62\,\mathrm{mm}^2$, $62 \times 62\,\mathrm{mm}^2$, $124 \times 62\,\mathrm{mm}^2$ and few narrow sensors around the beam-pipe
- **Thickness** $300\,\mu\mathrm{m}$ $\pm 15\,\mu\mathrm{m}$ (alternative thickness is being considered)
- **Pitch size** $58\,\mu\mathrm{m}$ on the both
- In-build AC coupling to the r/o
- Survive non-ionising dose 10^{14} $_{1\,\mathrm{MeV}}\,\mathrm{n_{eq}}$
- Full depletion voltage $60 - 80\,\mathrm{V}$



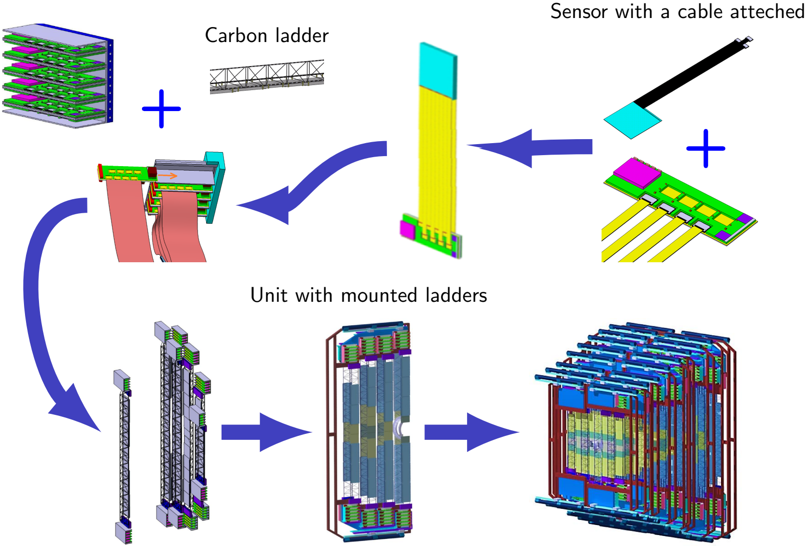
Mechanical setup



- Tracker is organised in **8 tracking stations**
  - each station has an individual layout
  - stations separated by $\approx 10\,\mathrm{cm}$
  - two aluminium C-frames per station
  - front-end electronics on top and bottom
    - bi-phase $\mathrm{CO_2}$ cooling down to $-40\,^{\circ}\mathrm{C}$
- Sensors are mounted on the light-weight **carbon ladders**
- Read-out electronics attached with **aluminium-polyamide micro-cables** (copper is considered as an alternative)
  - 64 channels connected with 1 cable
  - 128 channels per one ASIC (odd + even)
  - 32 micro-cables per sensor

Dedicated procedures, techniques and tools must be developed and manufactured

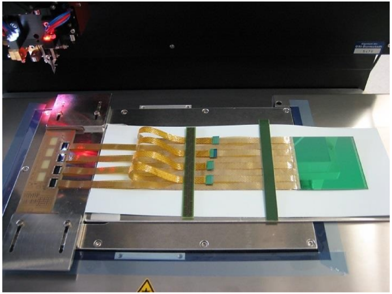
System integration

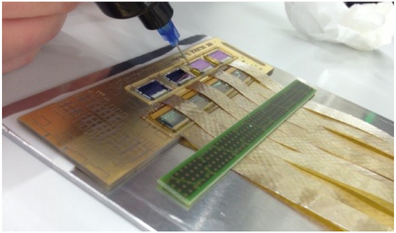


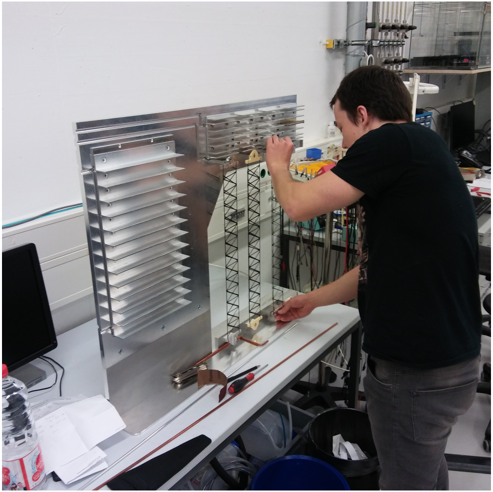
STS TDR - GSI Report 2013-4

Prototyping

Dummy module assembling:



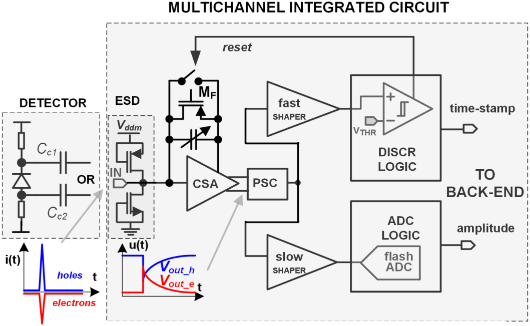




— mounting carbon ladders on the half-c-frame prototype

STS-XYTER ASIC

- STS data acquisition involves dedicated analog silicon integrated circuit
  - 128 channels per chip, 16 chips per micro-strip sensor
  - 5-bit flash ADC for each channel
  - time resolution $\leq 5\,\mathrm{ns}$



STS-XYTERv2.0 under test

Quality Assurance scheme

> 1000 sensors, > 32000 micro-cables:
to be tested on each stage of the integration

Pre-production stage: 100% of sensors tested at Quality Assurance Centers

Production stage: 5–10% + suspicious ones from optical inspection

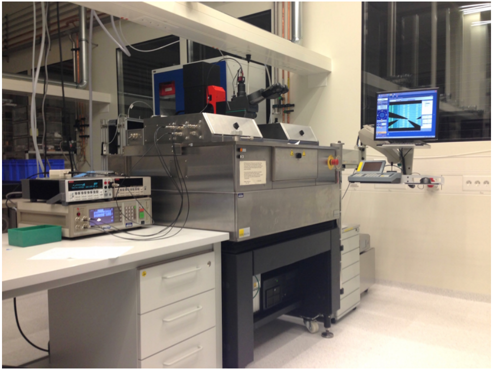
- 1% of sensors to be characterised in-depth (verify QA by vendors)

- QA centres:
  - GSI, Darmstadt
    - electrical tests
    - tests with radiation source (sensor R&D, module tests)
    - tests with infrared laser (sensor R&D, module test)
  - University of Tübingen
    - electrical tests
    - optical inspection
  - JINR, Dubna
    - electrical tests

Butches of sensors to be split between centres during mass production

Electrical tests

needle probe station @ GSI

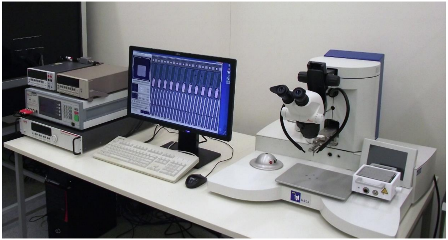


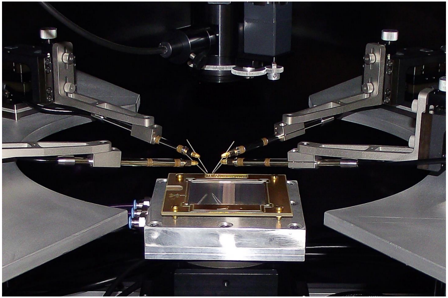
- Süss PA300PS probe station
  - $1\ \mu$m precision in X-Y-Z directions
  - chuck rotation (covers $\pm 7.5^\circ$)
  - temperature and humidity control
  - needles with $5\ \mu$m tips

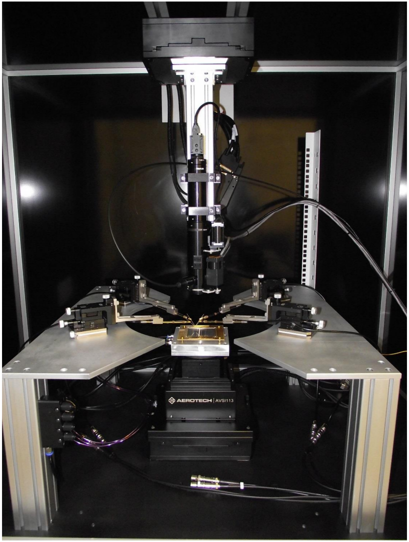
- Keithley 2410 SourceMeter $V < \pm 1100\,\mathrm{V}$, $\Delta I = 10\,\mathrm{pA}$
- Keithley 6487 **picoammeter/voltage source**, $I = 2\,\mathrm{nA} - 20\,\mathrm{mA}$, $V = 505\,\mathrm{V}$
- QuadTech 7600 precision **LCR-meter** $V_{\mathrm{bias}} = 500\,\mathrm{V}$, $f = (10^{-4} - 2)\,\mathrm{MHz}$, 0.05% accuracy
- Keithley 708B 8×12 **switching matrix** $\geqslant 1100\,\mathrm{V}$
- LabView based software:
  - pinhole
  - strip current
  - coupling capacitance...

Electrical tests

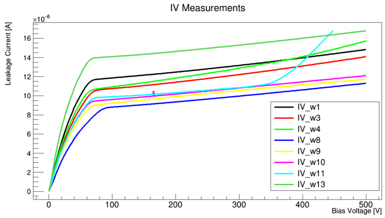
custom-made probe station in Tübingen University

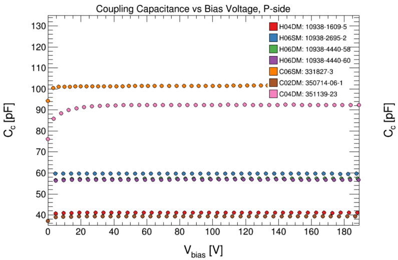


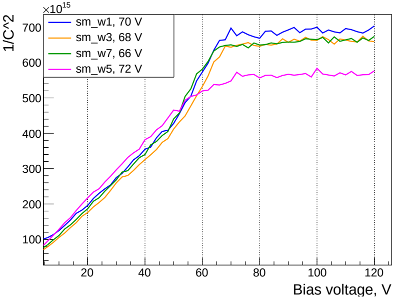


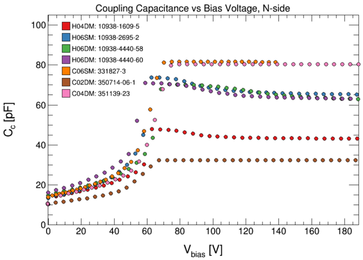


Examples of the electrical tests



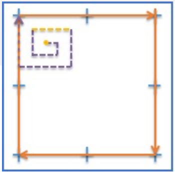


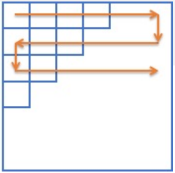


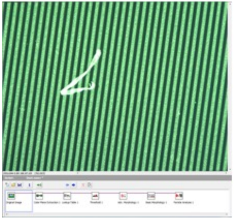


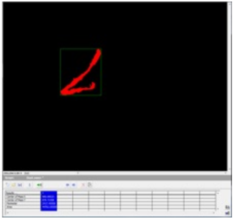
Optical inspection setup

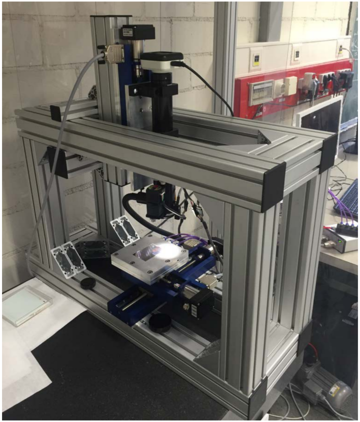
- Different objects can be studied (sensors in all sizes, micro-cables)
- Possible to detect:
  - **dust particles** and other foreign objects on the surface
  - **scratches**
  - single element integrity
    - bias resistors
    - strips, connection pads
    - guard ring
  - sensor **edge defects** & parallelity







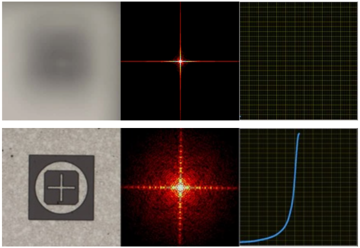


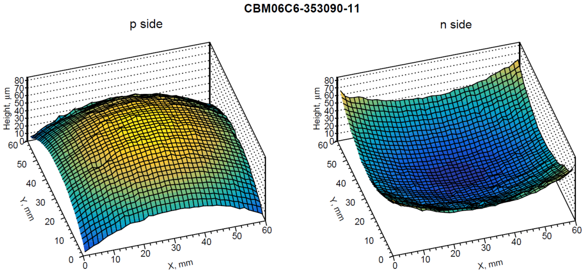


Optical inspection set up at Univ. Tübingen

Measurement of the sensor warp

- Contactless method
- Sensor surface curvature can be studied
- Procedure:
  - photos with different focusing distances
  - Fourier transformation
  - fitting with the Cauchy distribution
- Precision $\Delta z < 1\,\mu m$



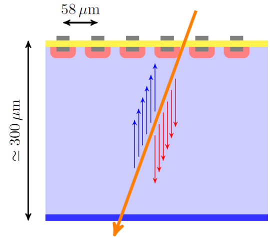


Laboratory tests

with radioactive sources

Charge collection efficiency $\varepsilon_Q = Q_{\text{registered}} / Q_{\text{induced}}$

- Electron-hole pairs to be created in sensitive volume
  - infrared laser (Si is transparent for $1060\,\text{nm}$ wavelength)
  - cosmic muons (MIPs in good approach but rare)
  - β **electrons** from Sc-90 isotope
    - high statistics
    - MIPs at $E_{kin} \geq 1.5\,\text{MeV}$
- Obey Landau-Vavilov distribution: $\Delta_p = 23 \pm 1\,\text{ke}^-$ for $300\,\mu\text{m}$ of Si
- Radioactive source setup:
  (non-)irradiated sensor in supporting PCB
  r/o electronics
  plastic scintillator + PMT for triggering
  cooling system + thermal enclosure
  ($T \simeq -10$℃)

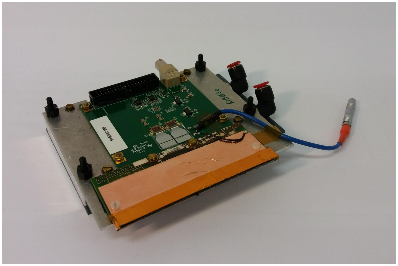


Detection efficiency $\varepsilon_{\text{det}} = N_{\text{registered}} / N_{\text{passed}}$

- Require tracking or reference detector

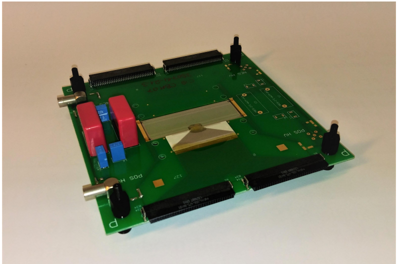
PCB design + customised electronics

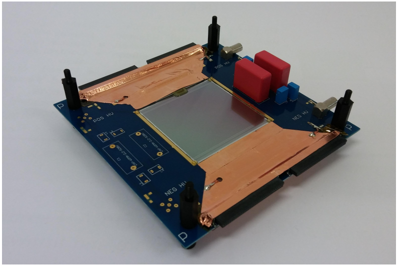
Alibava Daughterboard



- Support PCB was designed to fit r/o electronics
  - 2×64 channels $+2 \times 4$ ground pins — 2 ERNI connectors
  - $140 \times 140 \times 1\,\mathrm{mm}^3$ two sided PCBs
  - 3 layouts: 2, 4, 6 cm wide hole
  - on-board RC-LC filter
  - both p and n sides r/o from top-side
- Customised Alibava front-end board:
  - fan-out with 2×64 channels is attached

$62 \times 22\,\mathrm{mm}^2$ sensor

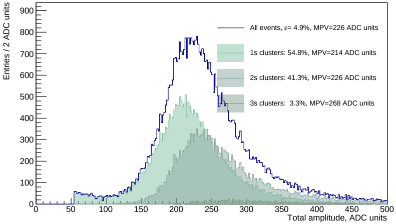


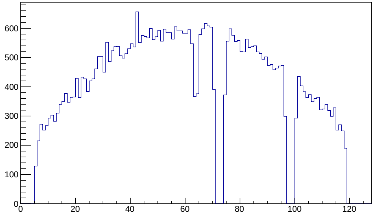


$62 \times 62\,\mathrm{mm}^2$ sensor

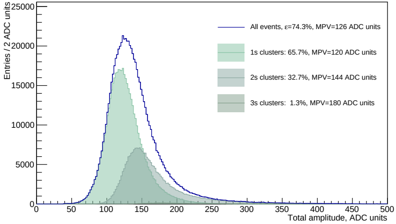
Amplitude spectra & hit maps

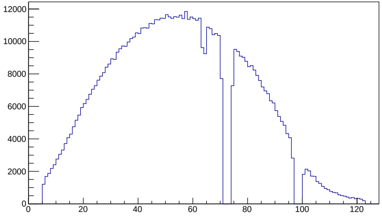
n-side, $62 \times 62\,\mathrm{mm}^2$ sensor





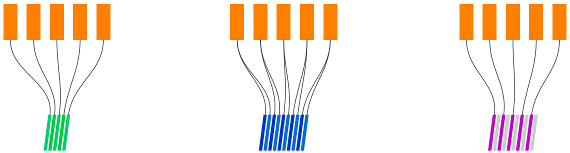
p-side, $62 \times 62\,\mathrm{mm}^2$ sensor





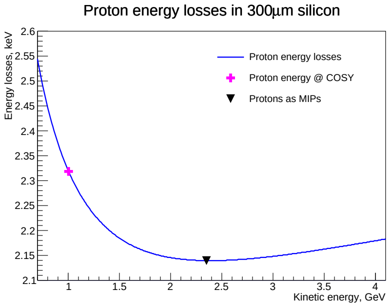
Alternative connection schemes

- **Geometrical effects** on the S/N ratio
  - $S/N \propto 1/\sqrt{n_{\text{strips}}}$, where n_{strips} is a cluster size
  - cluster size depending on angle (neglecting cross-talk):
    - $0^\circ \leq \theta \leq 11^\circ$, $n_{\text{strips}} \leq 2$
    - $11^\circ < \theta \leq 21^\circ$, $2 \leq n_{\text{strips}} \leq 3$
    - $\theta \geq 21^\circ$, $n_{\text{strips}} \geq 3$
  - S/N deteriorates by factor of $\sqrt{3}..\sqrt{4}$ for peripheral ladders
- **Geometrical solution**: (effectively) increasing strip width
  - change sensor mask pattern (cost and time consuming)
  - introduce alternative connection schemes to r/o electronics:
    - two strips to one r/o channel, $2 \to 1$
    - every second strip omitted, $2 \to 0$



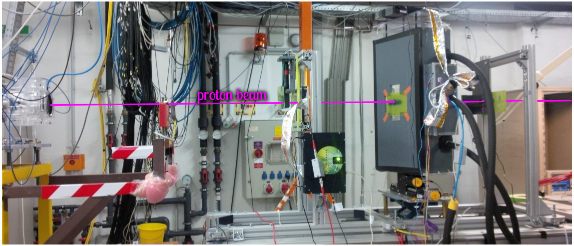
Motivation for the beam tests

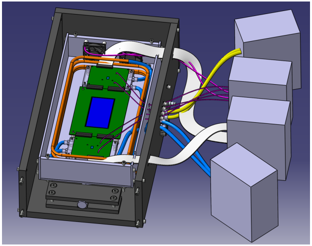
- Relativistic protons **(close to the real experiment conditions)**
  monochromatic: predictable $\Delta E/\Delta x$
  low momentum spread: good for angular studies
- **COSY** proton synchrotron in Jülich, Germany
  [R. Maier, NIM Volume 390, Issues 1–2, 1 May 1997, Pages 1–8, ISSN 0168-9002]
  kinetic energy $E_k = 1\,\text{GeV} \pm 1‰$ in August 2016
  crossing angle $\phi < 0.5^\circ$ (limited by station positioning precision)
- Studies of the charge collection efficiency
  - $$\frac{\Delta E(1.7\,\text{GeV}/c)}{\Delta E_{\text{MIP}}} = 1.08(4)$$
- Limited scattering in the material
- High statistic: up to $10^8/\text{s}$



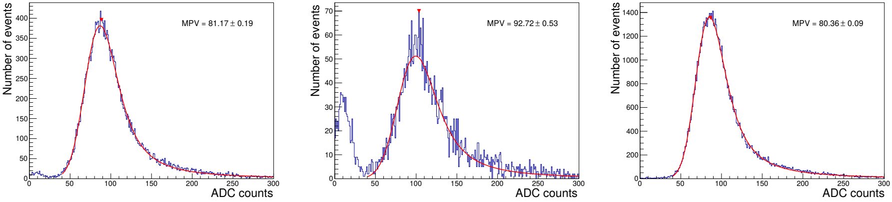
Beam tests @ COSY

Photo of the beam setup in Jessica cave; drawing of the thermal station





Preliminary charge spectra at zero angle for diff. connections $1 \rightarrow 1$, $2 \rightarrow 1$, $2 \rightarrow 0$:



Conclusions and outlook

- STS is actively developed by the wide international collaboration **from Germany, Poland, Russia and Ukraine**
- Tools and procedures for the **installation of the components** are in progress
- Dedicated `STS-XYTER` read out chip is being tested
- Various **QA procedures** are foreseen:
  - optical inspection
  - electrical tests
  - radioactive source setup and laser stand for modules
- Silicon **sensors are tested** for charge collection and detection efficiency
  - infrared laser stand (currently being developed)
  - radioactive source
  - proton beam @ COSY (Jülich, Germany)

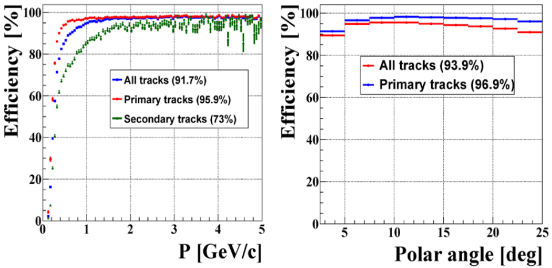
- Construction of STS in 2018–2021

Back-up slides

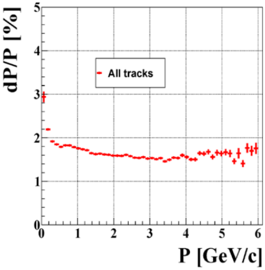
STS tracking performance

- detailed, realistic detector model based on tested prototype components
- CbmRoot simulation framework
- using Cellular Automaton / Kalman Filter algorithms

track reconstruction efficiency

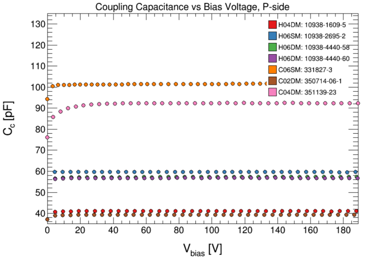


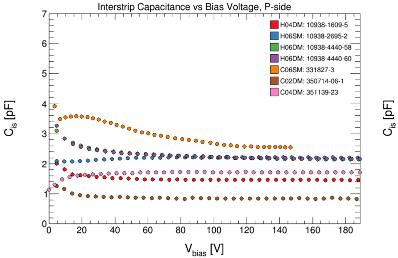
momentum resolution

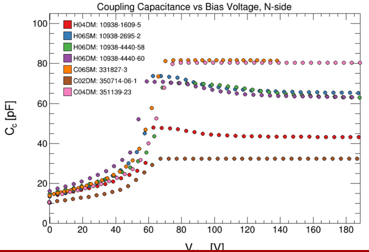


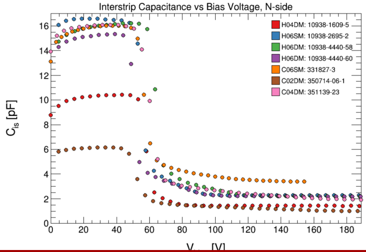
Individual strip tests in Tübingen University

interstrip capacitance vs bias voltage









Individual strip tests in Tübingen University

interstrip capacitance per strip