Karlsruhe Institute of Technology

Novel production method for large double-sided microstrip detectors of the CBM STS

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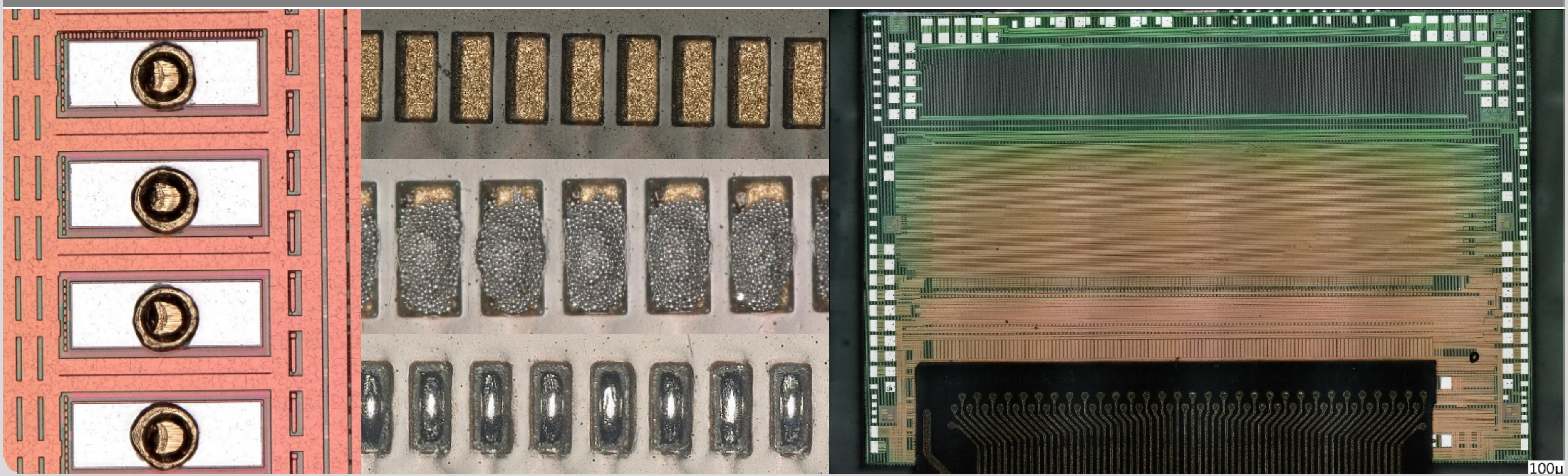
for the CBM collaboration

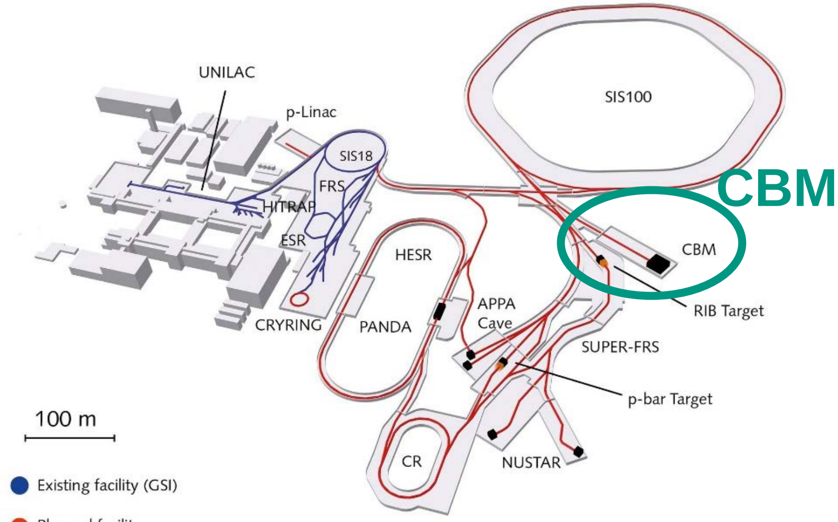
Institute for Data Processing and Electronics



Outline

- Compressed Baryonic Matter (CBM) experiment @ FAIR
- Silicon Tracking System (STS)
- Detector module conception and its challenges
- Detector module production based on TAB bonding
- Novel detector module production approach based on Au stud – solder bump bonding

Facility for Antiproton and Ion Research (FAIR)



https://www.gsi.de/fileadmin/_processed_/8/9/csm_FAIR-beschriftet_MSV_DE_Feb18_4408267c7b.gif

https://res.cloudinary.com/wired-de/iu/s--5kacTFBm--/c_fill,f_auto,h_450,q_auto:good,w_900/fair_gsi_credits_fairjan_schafer.jpg.jpg

- CBM one of the major scientific programs at FAIR
- highest baryon densities at still moderate temperatures

https://fair-center.de/typo3temp/pics/5510babc84.jpg

Link to drone video of FAIR construction site

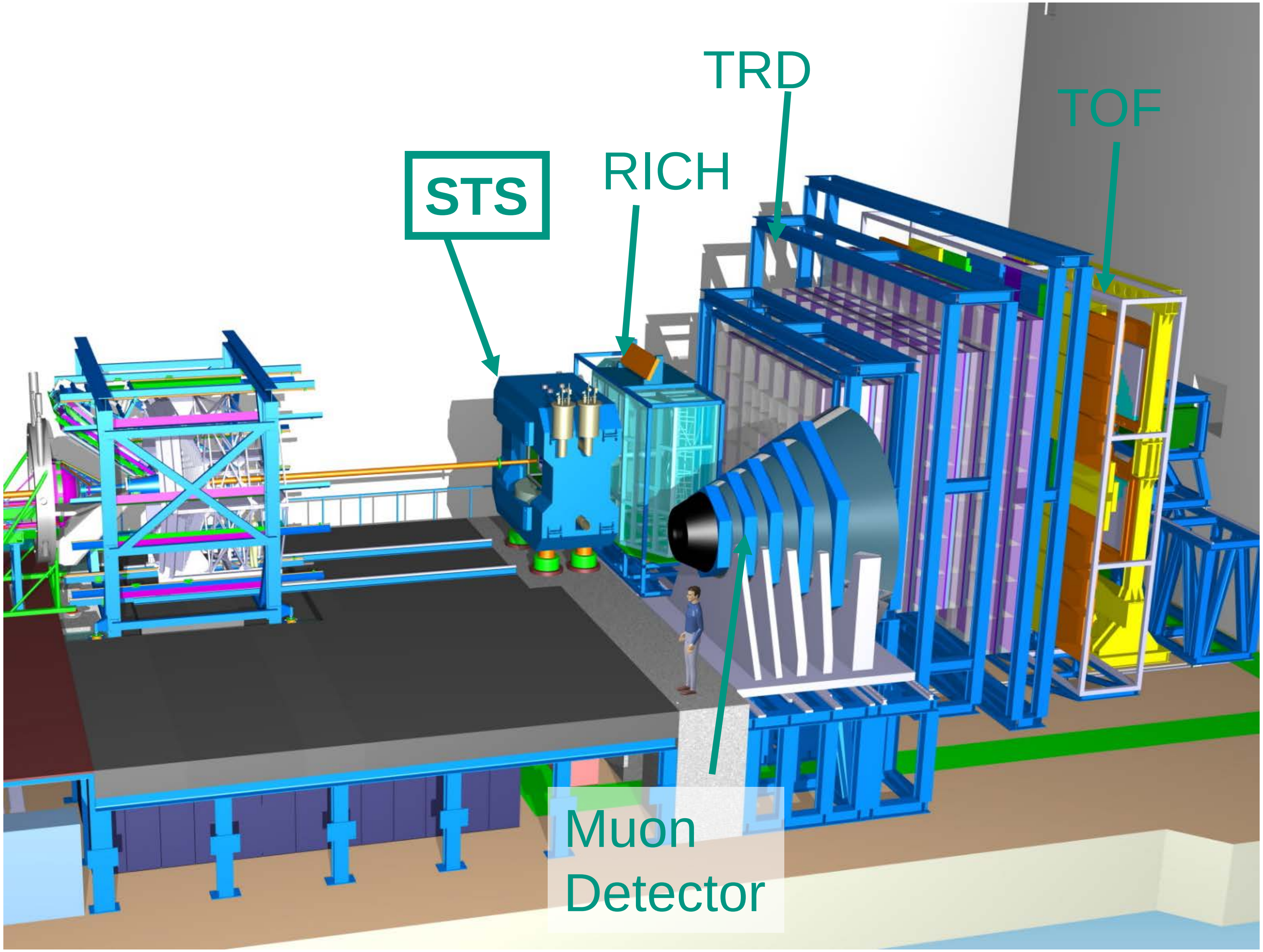
⇩

https://Drone video of FAIR construction site June 2018-

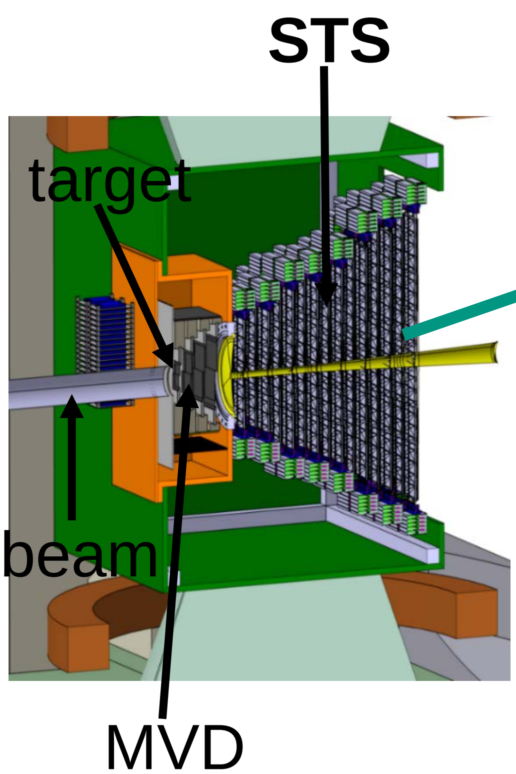
CBM experiment at FAIR

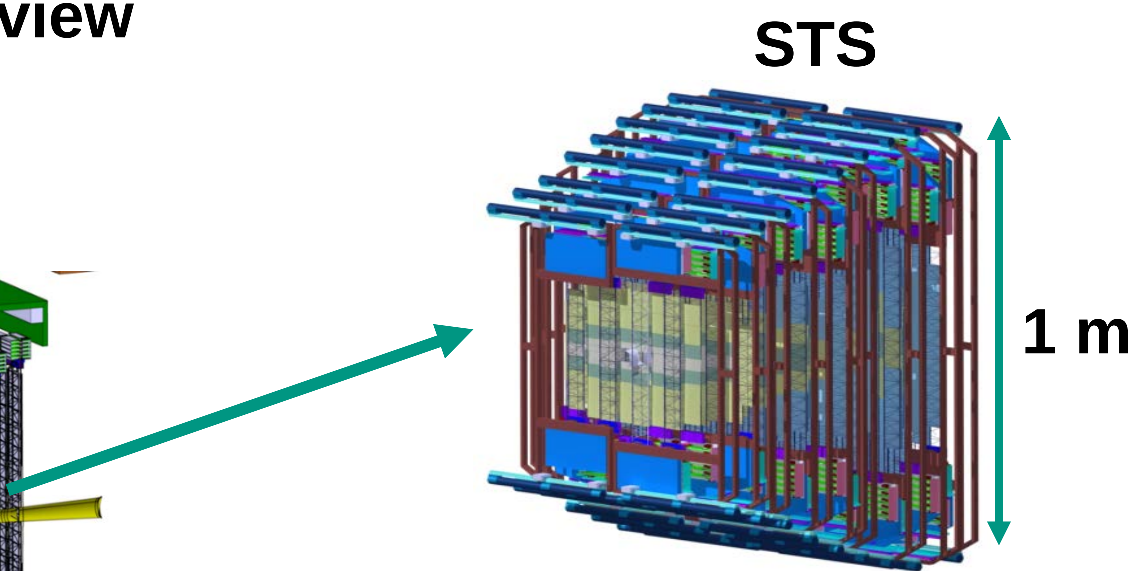
- Heavy ions, especially Au
- High rate, fixed target
- Unprecedented precision and statistics
- Exploration of new energy range

CBM detectors



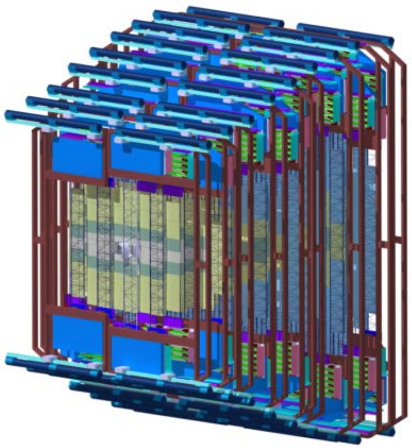
STS system view



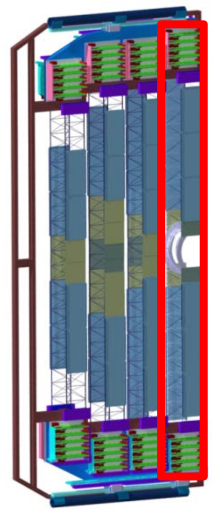


- Eight tracking stations 0.3 m to 1 m downstream of the target
- Total sensitive area $\approx 4\ \mathrm{m}^2$
- Very low material budget
  - per station: $X/X_0 < 1\%$
- Lifetime fluence $1 \times 10^{14}\ \mathrm{n_{eq}cm^{-2}}$

STS structure



Half-station

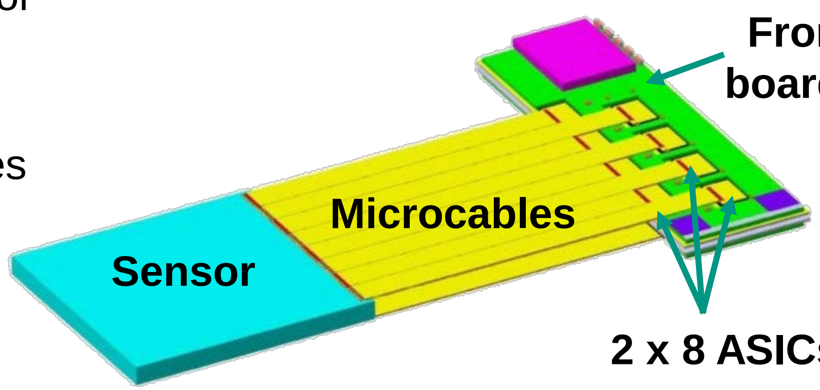


Ladder

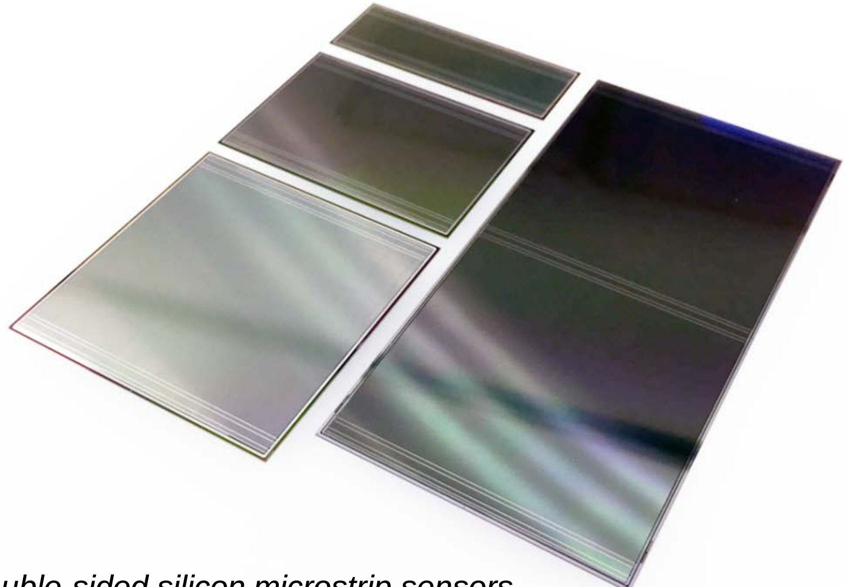
- 17 ladder variations

Detector module

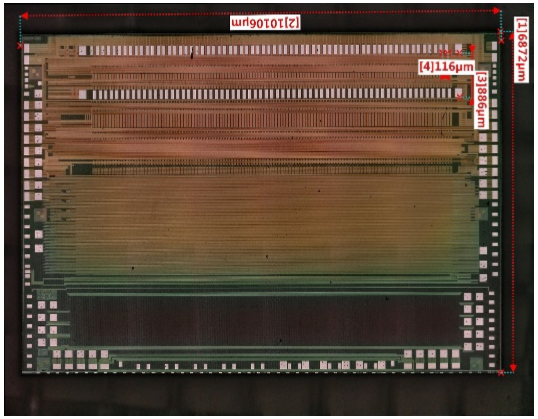
- Double-sided microstrip sensor
  - Pitch: 58µm
  - 2 x 1024 channels
- 2 x 8/16 low mass microcables
- 2 x 8 STS-XYTER ASICs
- 2 FEB-8



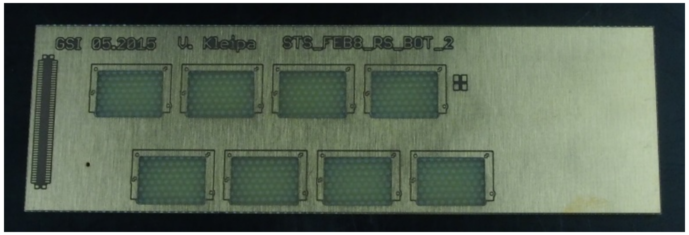
Module components



Double-sided silicon microstrip sensors. Thickness: 300 µm. Sizes: 62 mm x 22, 42, 62, 124 mm



STS-XYTER readout ASIC with 128 channels. Size: 7 mm x 10 mm



FEB-8 readout board dummy

Low mass microcables with varying length. Top: single cable. Bottom: sheet of 8 cables. Pitch:116 µm

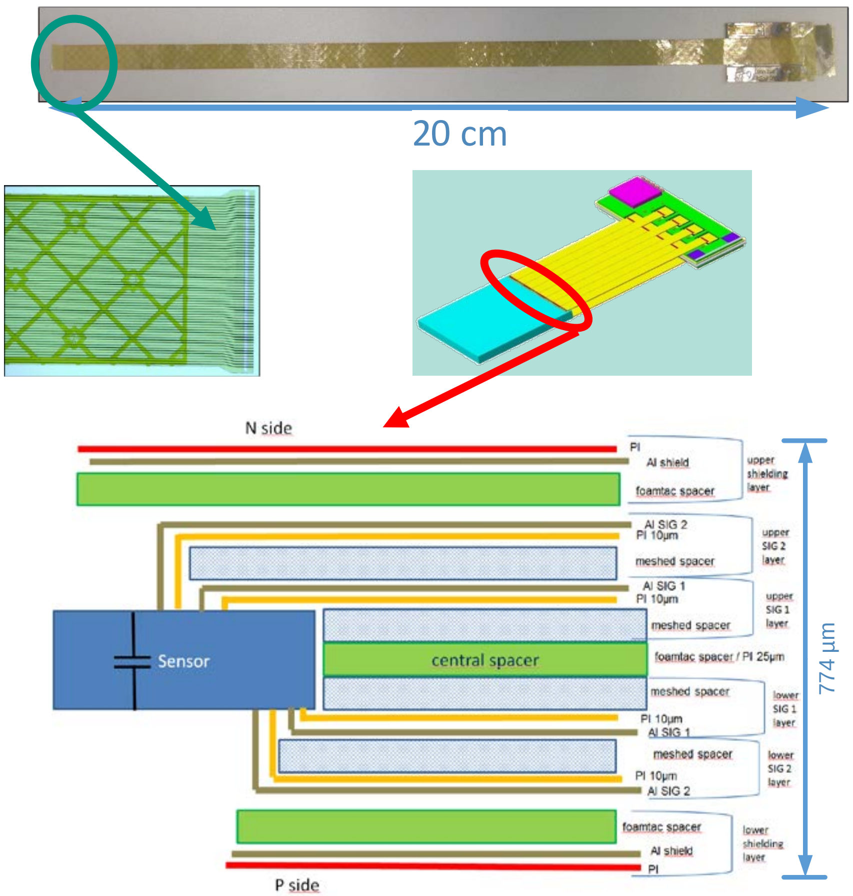
STS numbers

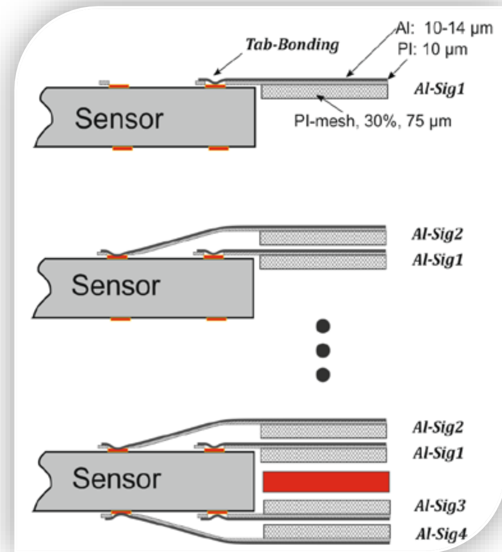
Part	Quantity
Stations	8
Ladders	106
Modules	896
Frontend boards (FEB)	1792
STS XYTER ASICs	14 336
Microcables	14 336 or 28 672
Channels	1.8 million

- Three module production centers
  - JINR (50 of 120 %), stations 1 - 4
  - KIT (40 of 120%), stations 5 - 8
  - GSI (30 of 120 %), stations 5 - 8
- Module production schedule: Sep. 2019 – June 2021
- Detector finished beginning of 2024

Module assembly: Al – Al TAB bonding

- 64 channels with 116 µm pitch
- 15 µm Al on 10 µm PI

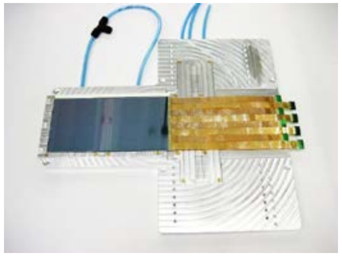




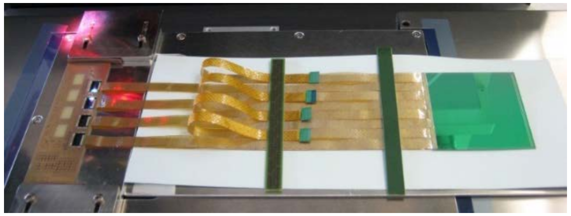
Assembly workflow

- Capacitance < 0.5 pF/cm
- $X/X_0 \sim 0.03$ %
- Room temperature process
- 32 cables per sensor
- Partial reworking

Module assembly: TAB bonding @ GSI

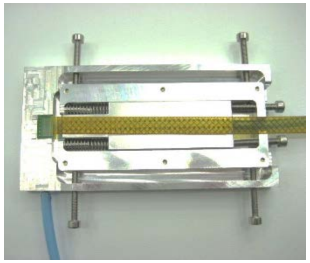


Sensor-side bonding

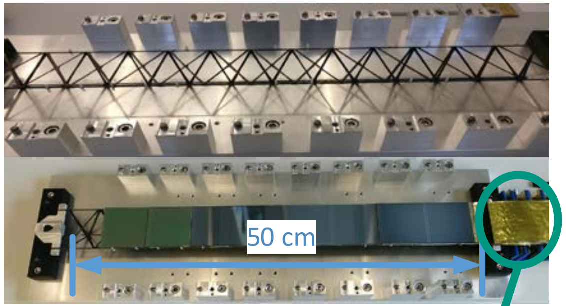


Glueing ROCs on FEB-8

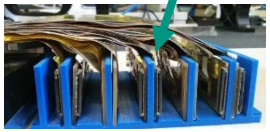
Dummy modules with shielding



ROC-side bonding



Carbon ladders before (top) and after (bottom) module mounting

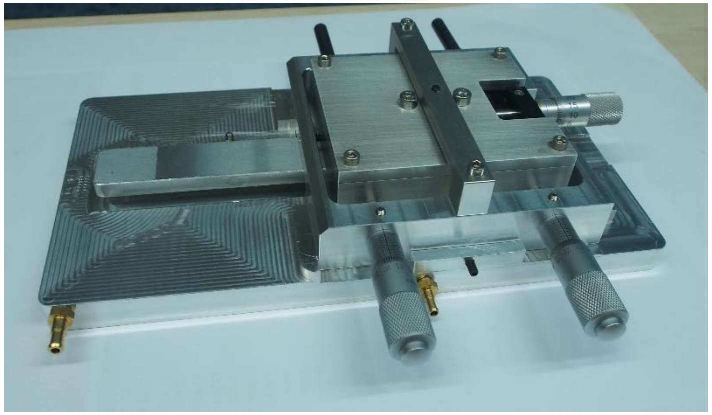


FEB-8 boards

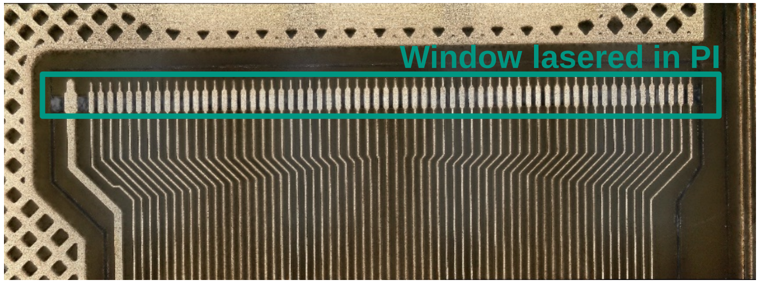
- Well-established, several full modules with different cable lengths and sensor sizes built and integrated into light-weight carbon ladder frame
- Manual procedure
- Single supplier in Kharkov, Ukraine

Module assembly: Cu - Al TAB bonding

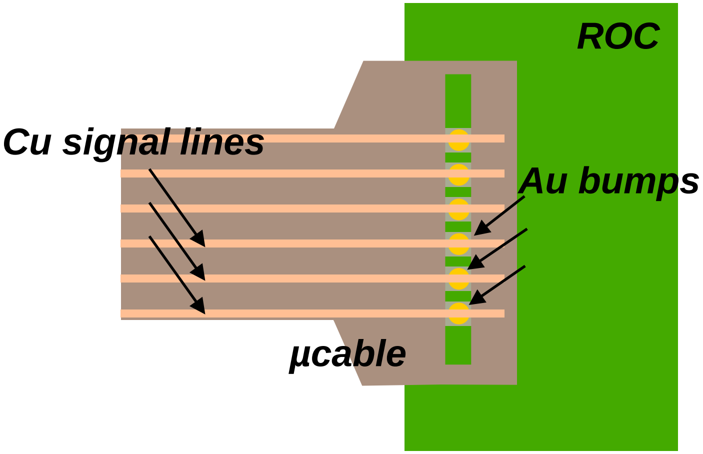
- More industry experience with Cu
- Combining several cables possible due to higher yield
  - Less complex assembly
- Cu is hard, can destroy bond pad
- Cu - Al TAB bonding requires temperature, which leads to increased oxidation
  - Idea: TAB bond on Au bumps



TAB bonding jig



Copper microcable designed for TAB bonding

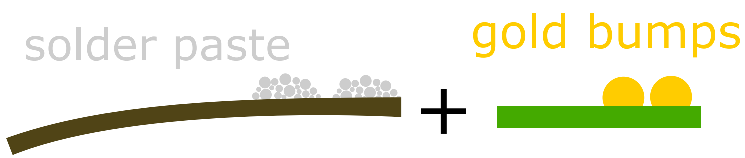


Schematic top view of TAB bonding on Au bumps

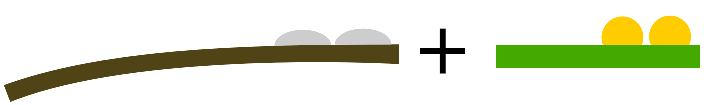
Novel approach: Gold stud – solder process

1. cable and chip

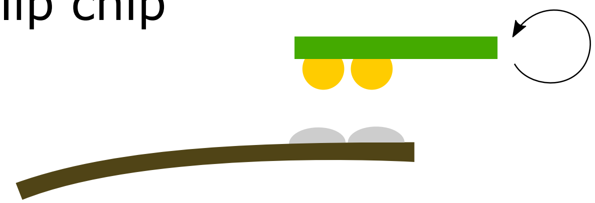
2. place bumps on chip and solder paste on cable



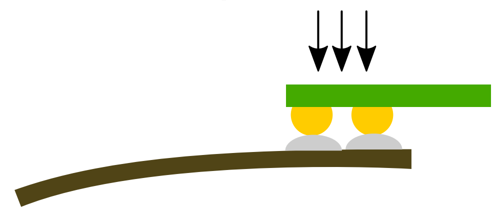
3. reflow



4. flip chip

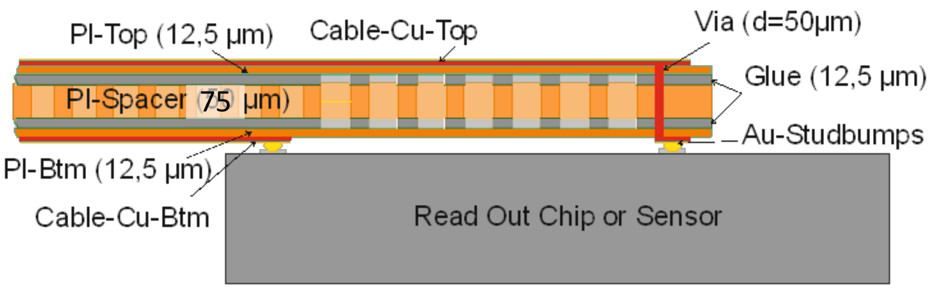


5. thermocompression bonding

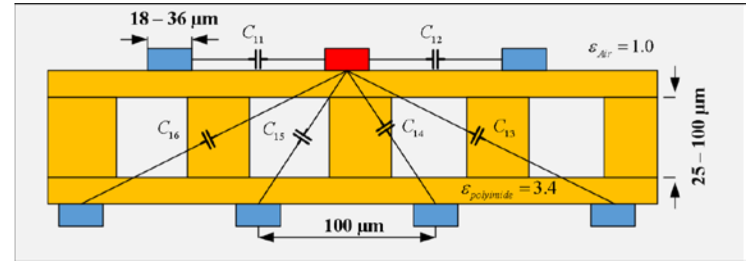


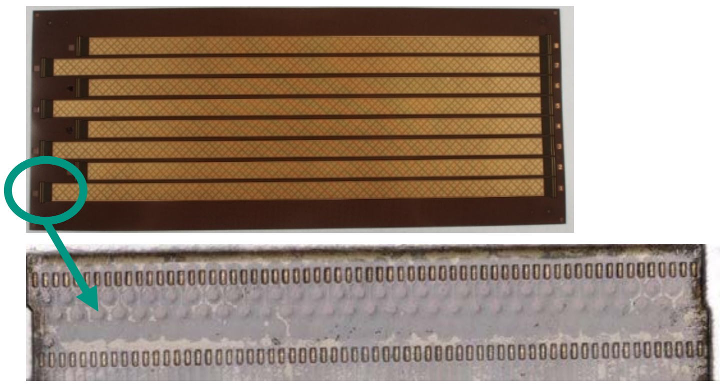
6. underfill

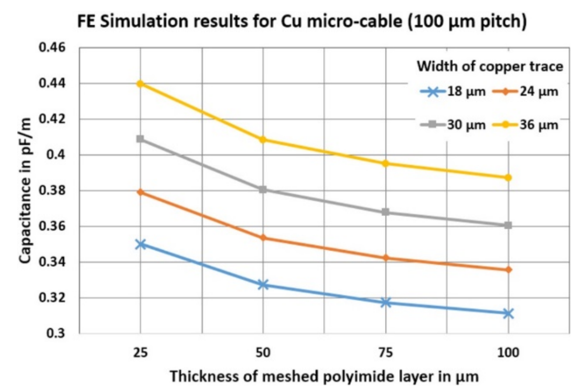
Copper microcables for Au-solder process



FEM simulation (COMSOL)





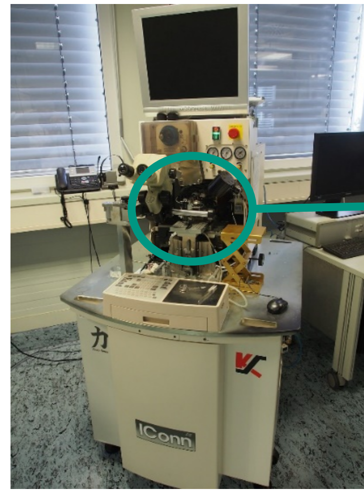


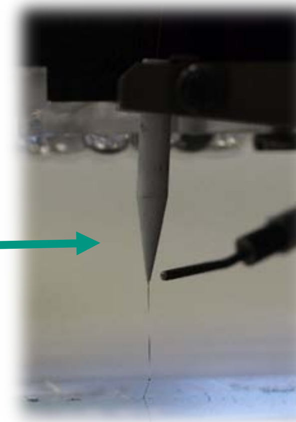
- Alternative assembly solution
- Higher degree of automization
- Reworking of full cable

- Double layered: half amount of cables needed
- Capacity ~ 0.44pF/cm
- X/X_0~ 0.05 %

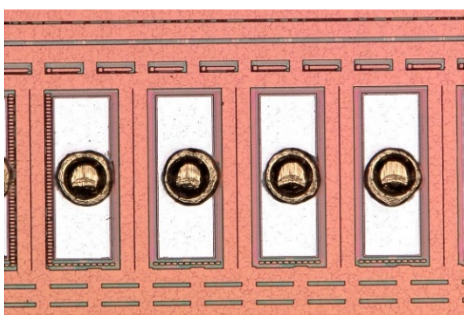
ROC and sensor side: Gold stud bumping

- Iconn ball wire bonder
  - 20 bumps/s
- STS parameters
  - 25 µm Au wire
  - Bump diameter 60 µm
  - Bump height: 30 µm

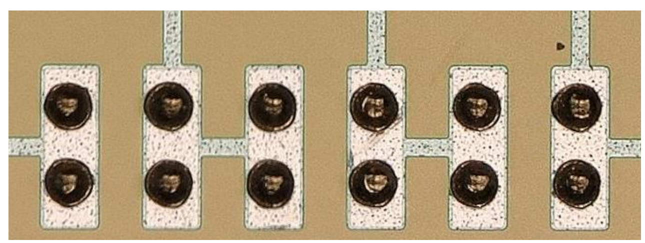




Capillary with Au wire



Gold bumps (diameter 60 µm) on STSXYTER



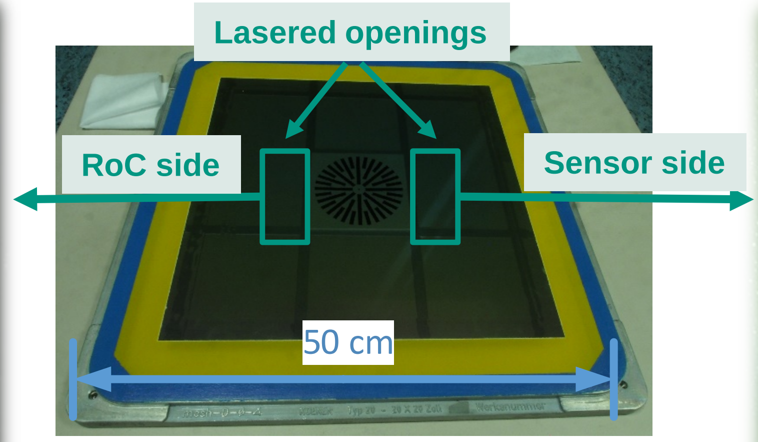
Double balls to improve mechanical strength

Au bump on top of another Au bump

Fast, flexible, reliable

Cable side: Solder printing and reflow

Solder printing machine



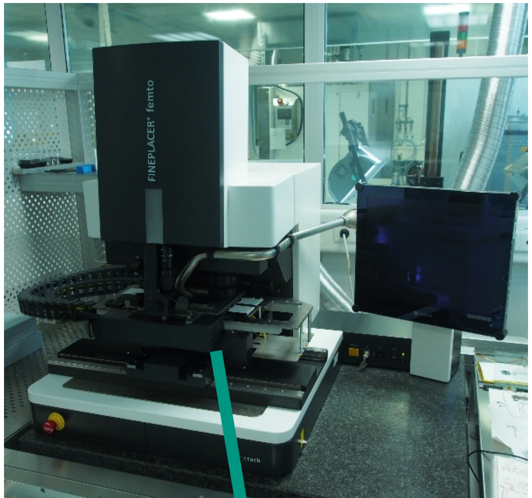
40 µm stainless steel stencil to print 8 cables simultaneously

1. Bond pads with Au surface finish

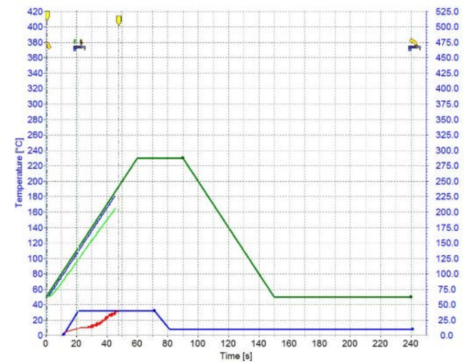
2. After printing type 7 solder paste

3. After reflow of the solder paste

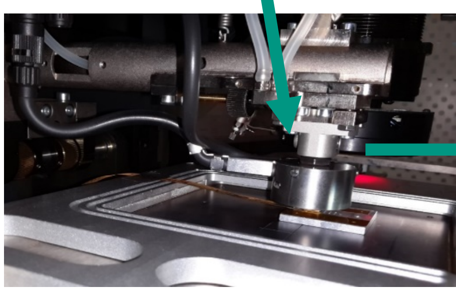
1st interconnection: ROCs on µcables



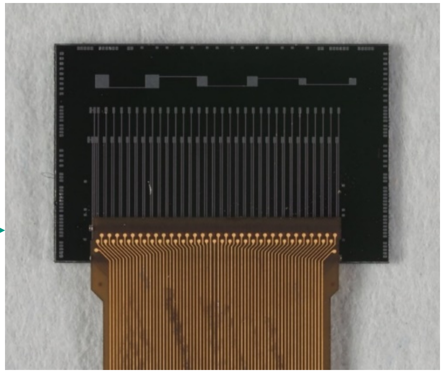
- Femto fineplacer flip chip machine (0.5 µm accuracy)
- ROC bonded onto µcable
- Thermocompression bonding process
  - F = 40 N
  - T = 230 °C



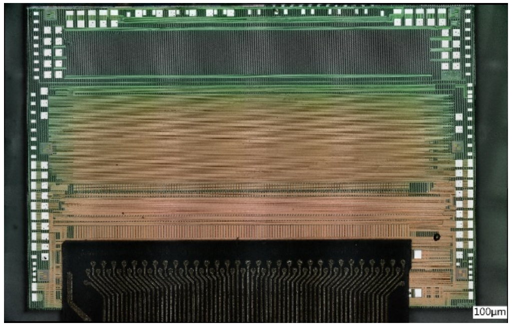
ROC-µcable bonding profile



Bonding process

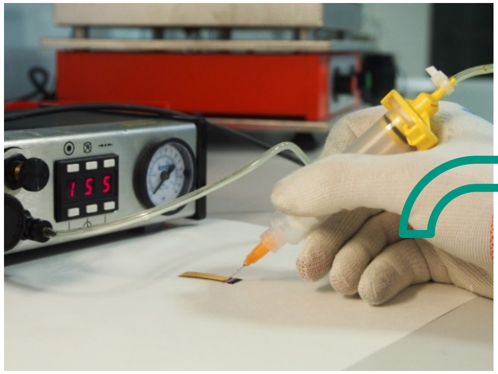


Cu µcable bonded on dummy ROC

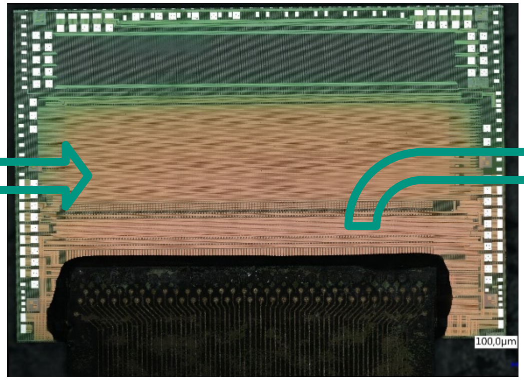


Microcable bonded on STSXYTER

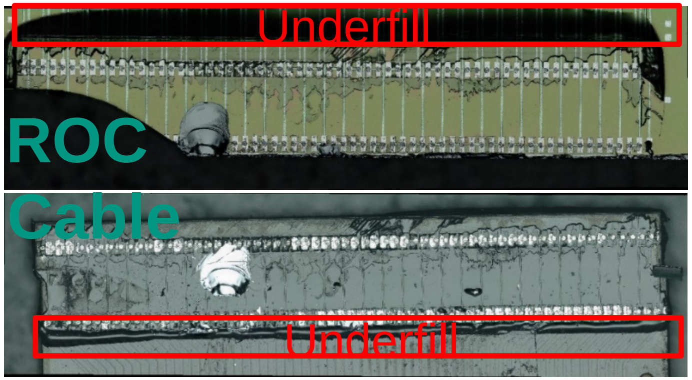
Underfill for spark protection and improved mechanical strength



Underfill application

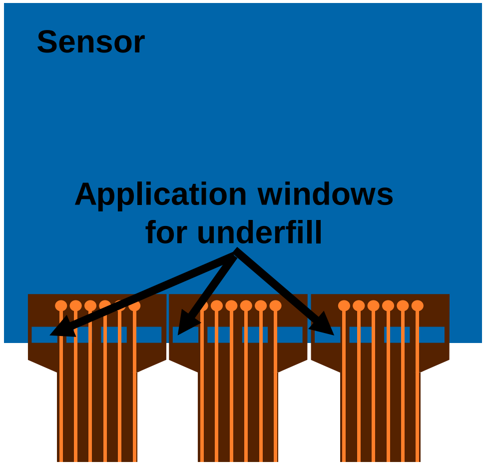


Cu cable on STSXYTER protected by underfill



ROC and cable after disconnection

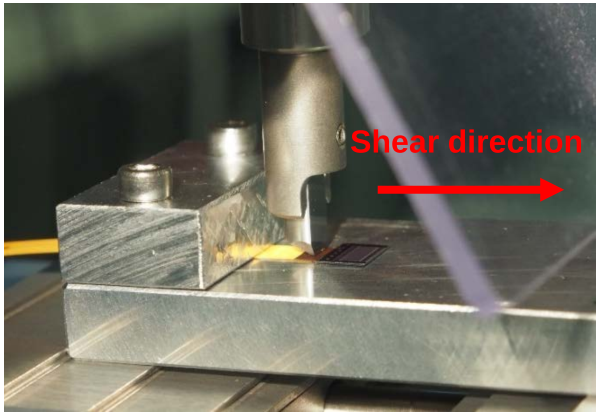
- LV cable has to be protected from HV on sensor edge
- Small gap ~ 20 µm, additional obstructions by gold bumps
- First tests with Polytec EP601-LV (Viscosity: 240 mPas) are encouraging
- Optimized cable layout for underfill application foreseen



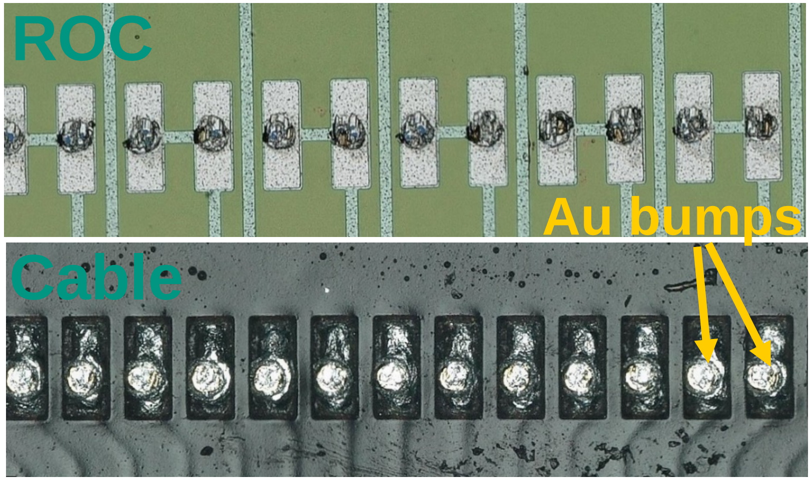
Improved cable design

High mechanical robustness

- Shear test: quantitative measurement of mechanical strength
- 2-3 kg shear strength without underfill
  - Ball lift-off ⇨ gold bump connection is the weak link, not Au-solder
- Optimization of bumping parameters should increase mechanical strength further
- Cable torn apart outside the connection area after application of underfill



Shear test setup. Cable is clamped down firmly while the shear tool shears the RoC



Shear test reveals that all Au bumps are lifted off the ROC

2nd interconnection: in-house bonding machine for sensor side

- Four stepper motors (x,y,z,φ) with sub-micron resolution
  - Bond force up to 100 N, force controlled by force sensor
- Temperature regulated heatable bond head and sensor plate
- Top and bottom camera
- Automated vacuum control
- Syringe for underfill application

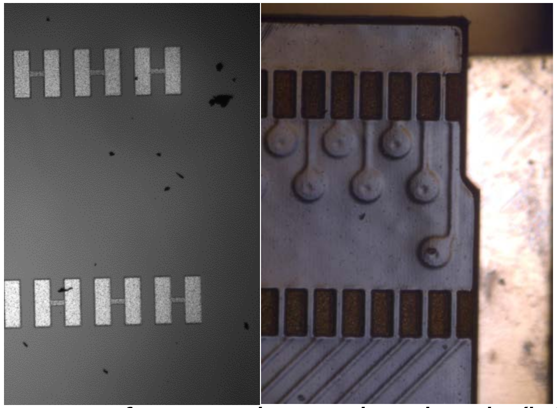
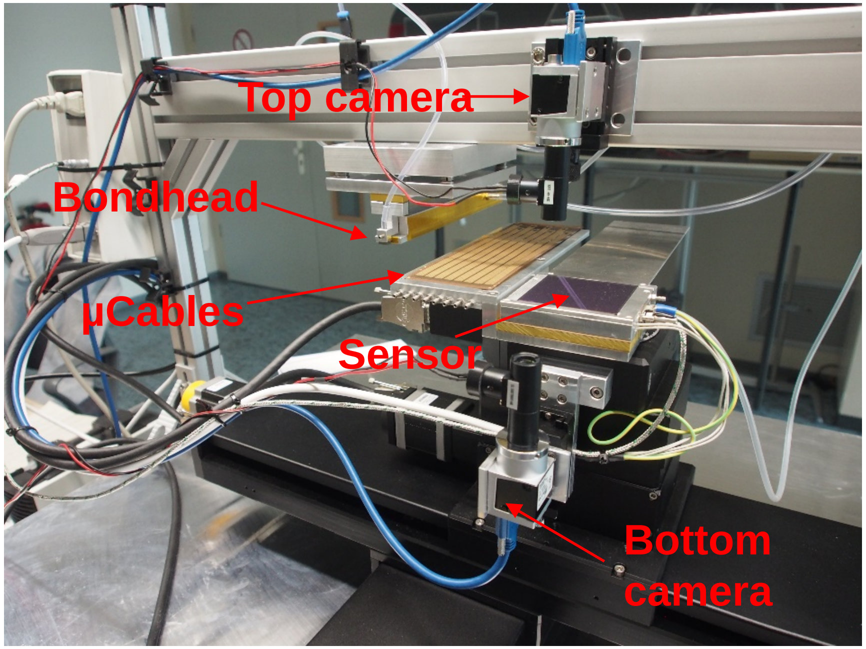


Image of sensor dummy bond pads (left) and cable bond pads (right) taken by implemented cameras



Summary

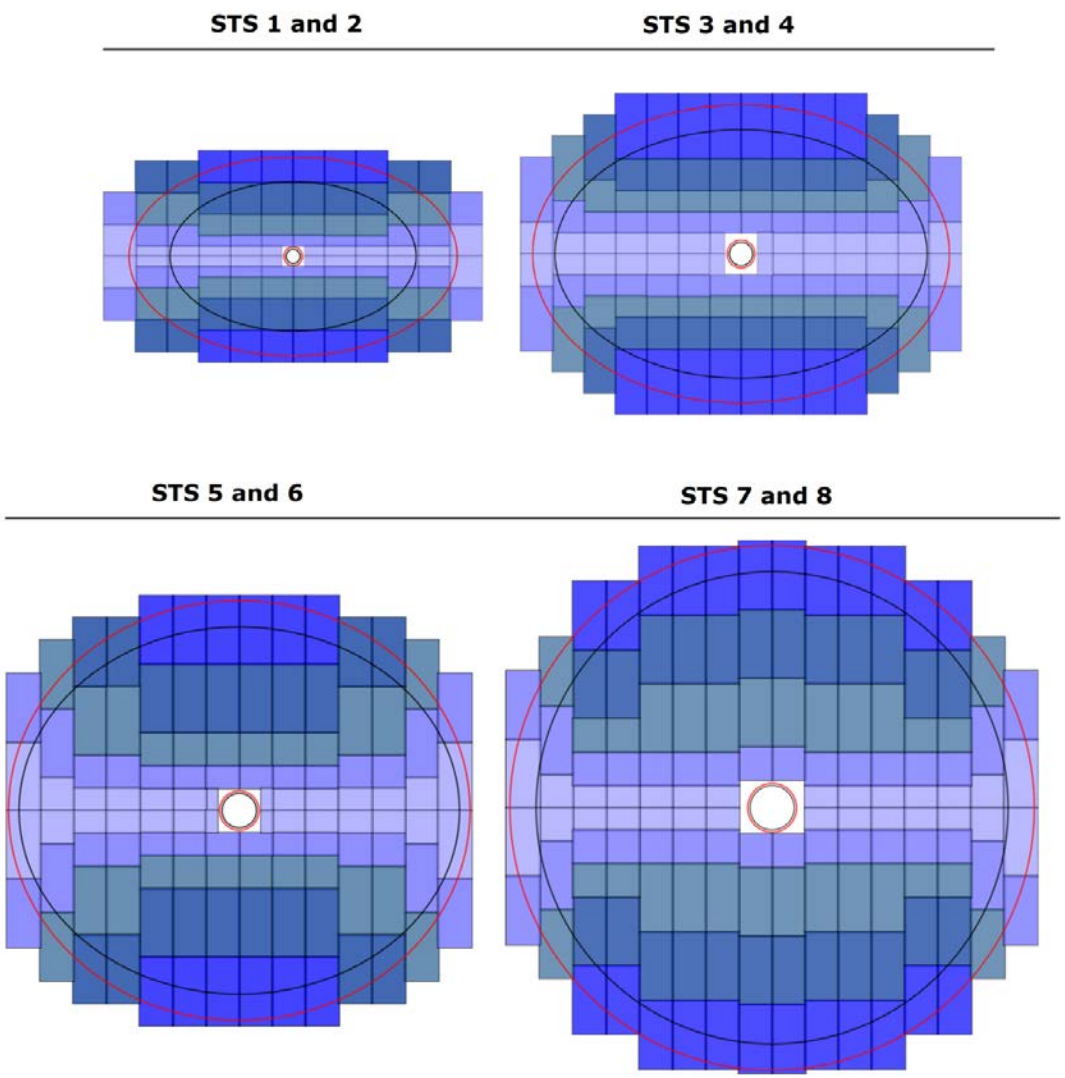
Karlsruhe Institute of Technology

- Very low material budget requirements for the STS force the readout electronics outside the beam aperture which leads to a complex detector module conception
- Detector module production is divided internationally between three institutes
- Al – Al TAB bonding as primary interconnection technology
- A novel high-density interconnection method for large double-sided microstrip sensors has been developed
- Au stud – solder process enables a new bonding technology of ASIC and sensor on flex microcable

Thank you for your attention!

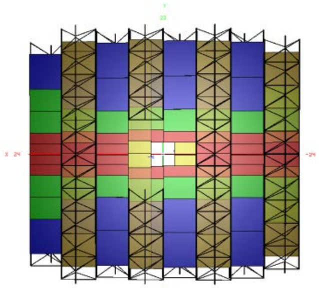
Backup slides

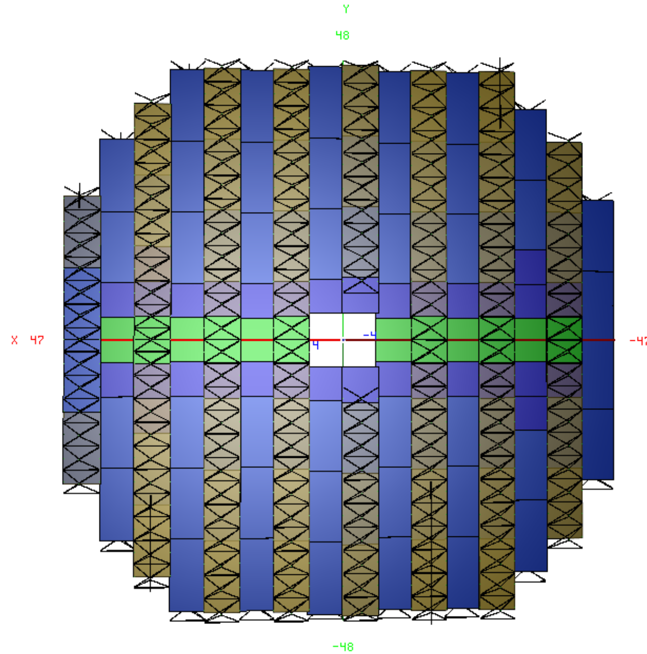
Station sizes



Sensor sizes

STS 1

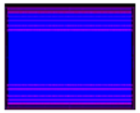




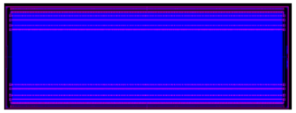
outer parts of large stations

standard sensors throughout the stations

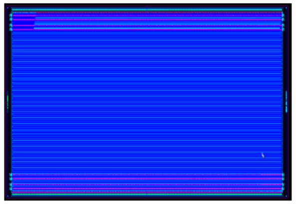
fill gaps at beam hole



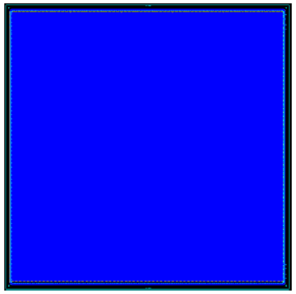
few sizes, small numbers



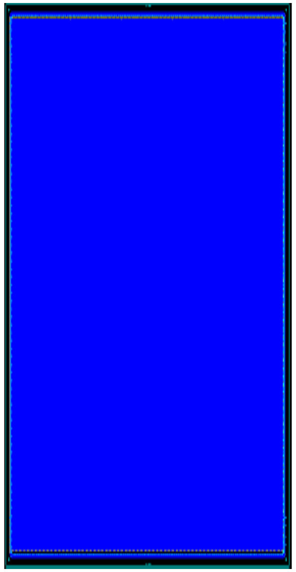
6.2 cm × 2.2 cm



6.2 cm × 4.2 cm

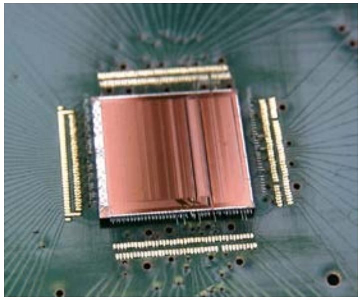


6.2 cm × 6.2 cm



strip length

6.2 cm × 12.4 cm



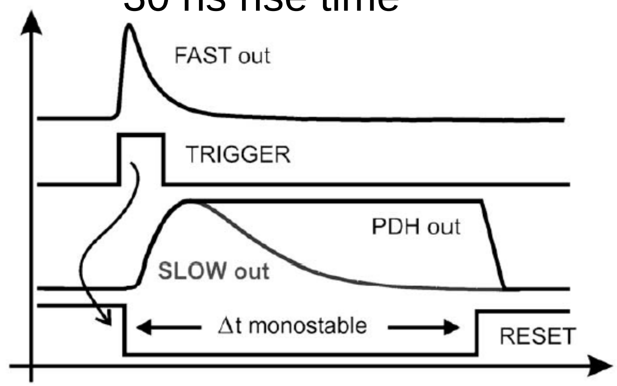
128 channels

n-XYTER chip

- from a neutron imaging project
- used for current prototyping (v1, v2.0)

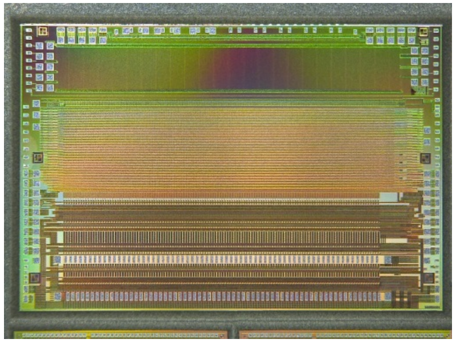
NIM A 568 (2006) 301–308

30 ns rise time



170 ns rise time

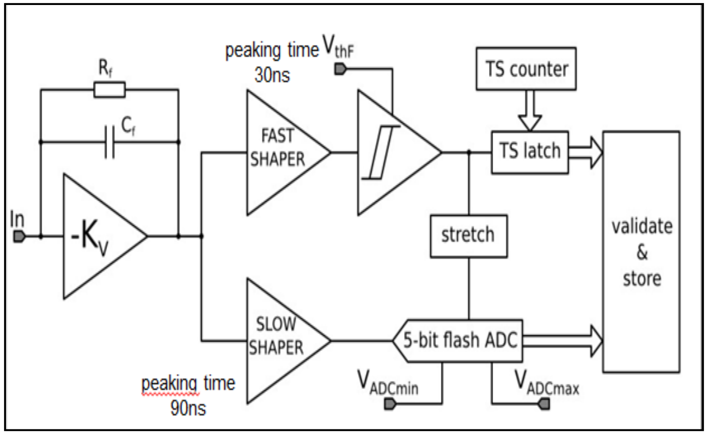
self-triggering: channels deliver stream of ADC values above threshold + timestamp



128 channel s

STS-XYTER chip

- dedicated development for STS, now v2.0



per channel: two-stage internal trigger

adapted to high capacitive load

back-end GBT compatible

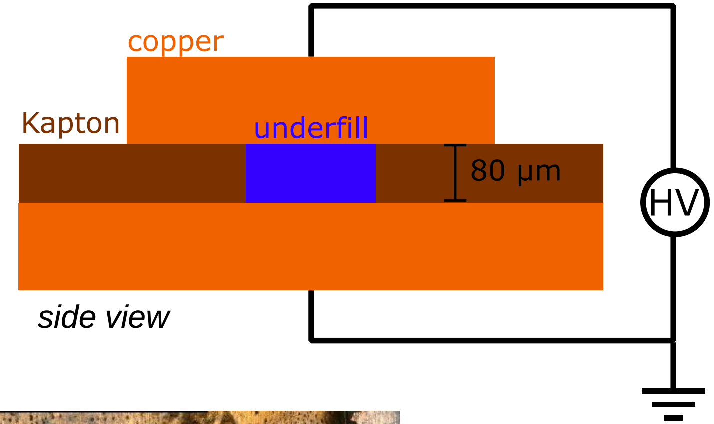
Silicon Tracking System (STS) design constraints

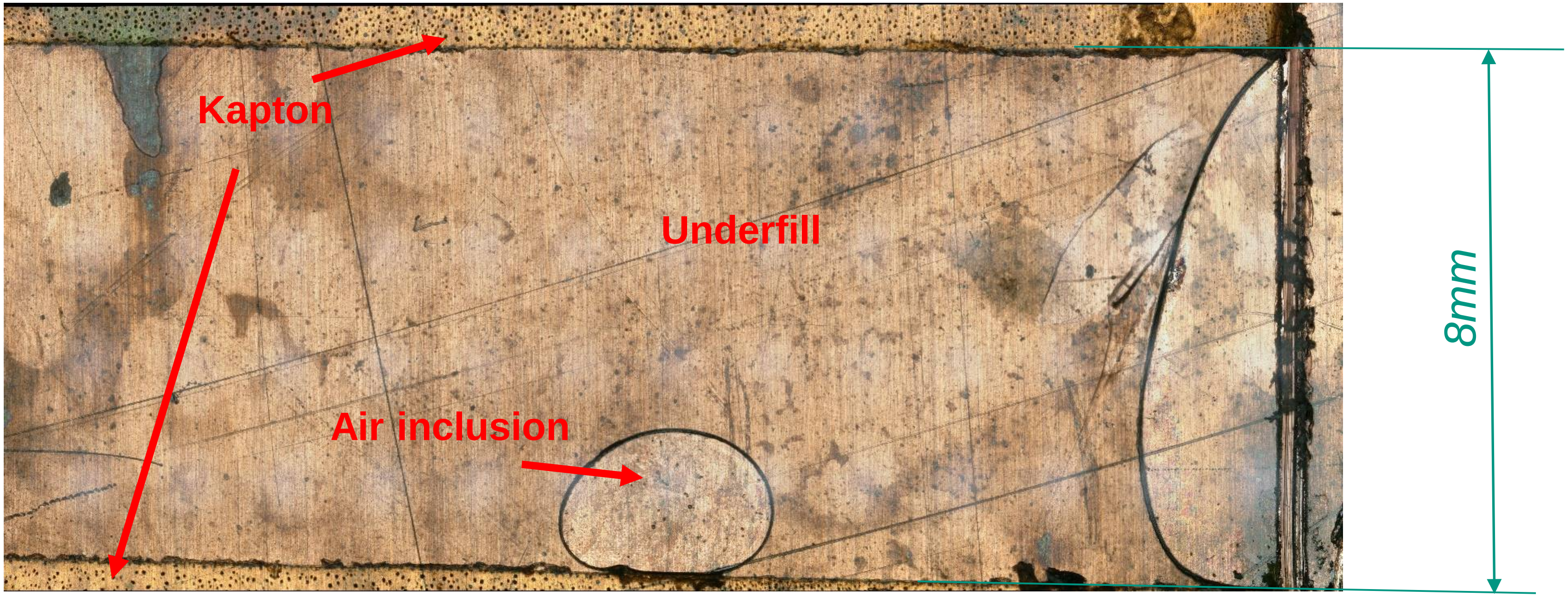
- Coverage
  - aperture 2.5° < Θ < 25°
- No event pile-up
- Efficient hit & track reconstruction
- Minimum granularity
  - largest read-out pitch compatible with the required spatial resolution
  - maximum strip length compatible with hit occupancy and S/N performance
- Radiation hardness
- Integration, maintenance
  - Confined space inside dipole magnet
  - Cooling
  - Extraction possibility
- Momentum resolution
  - $\Delta p/p \sim 1\%$
  - material budget per station 0.3 - ~1% X_0

⇨ Read-out electronics must be located outside the beam aperture!

Underfill breakdown test

- Polytec EP601-LV
- Breakdown at ≈ 1000VDC for properly cured underfill, even with air inclusions
- ≈ 300VDC for air only





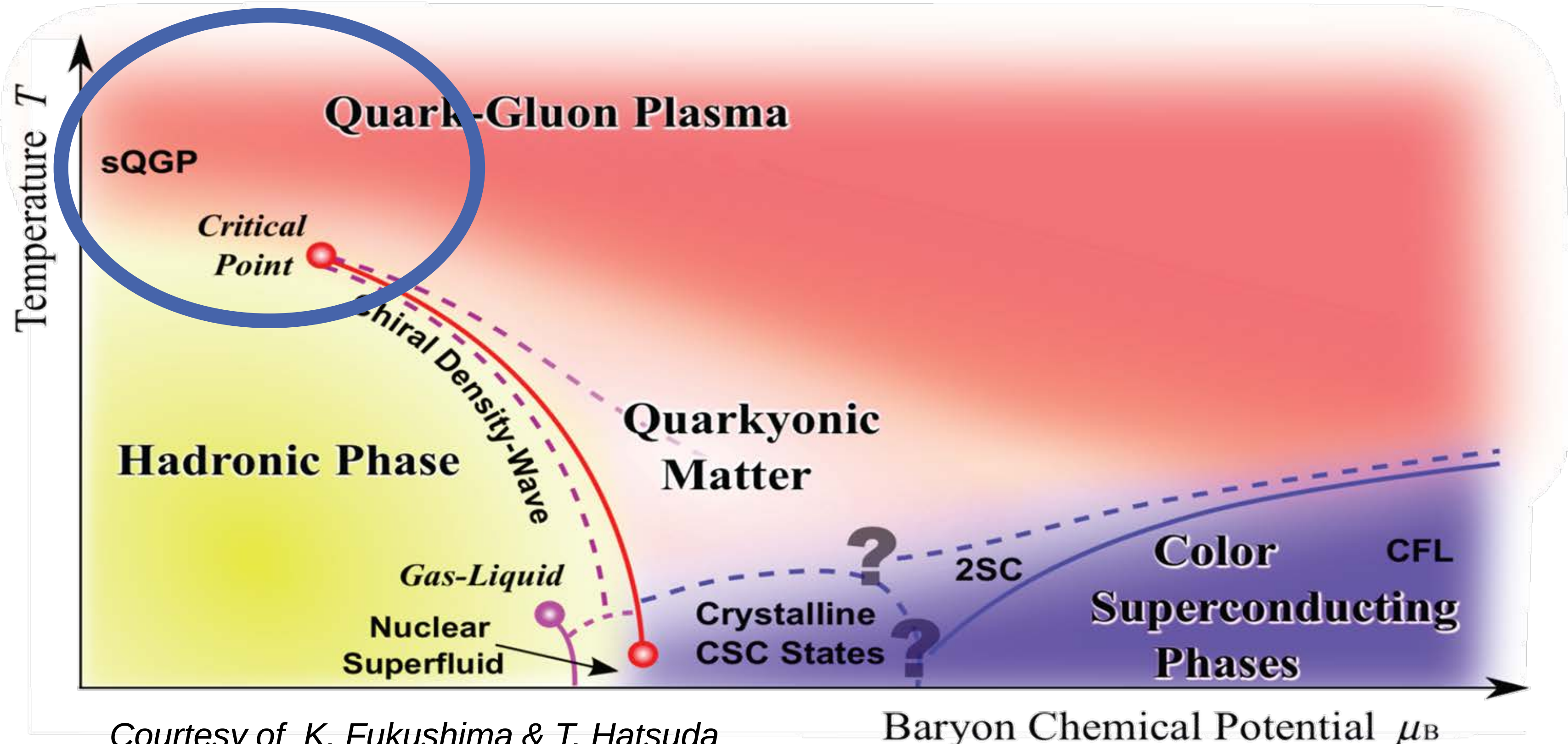
top view

Fundamental questions of QCD

- What is the equation of state of QCD matter at high net-baryon densities, and what are the relevant degrees of freedom at these densities? ($\rightarrow$ core collapse supernovae, neutron stars, early universe).
- Is there a phase transition from hadronic to quark-gluon matter, or a region of phase coexistence and a critical point? Do exotic QCD phases like quarkyonic matter exist?
- To what extent are the properties of hadrons modified in dense baryonic matter? Are we able to find indications of chiral symmetry restoration? ($\rightarrow$ origin of hadron masses, i.e. of the visible universe).
- How far can we extend the chart of nuclei towards the third (strange) dimension by producing single and double strange hypernuclei? Does strange matter exist in the form of heavy multi-strange objects?

QCD phase diagram at very high T

- N of baryons ≈ N of antibaryons; early universe
- L-QCD finds smooth crossover from hadronic matter to Quark-Gluon Plasma
- ALICE, ATLAS, CMS at LHC; STAR, PHENIX at RHIC



Courtesy of K. Fukushima & T. Hatsuda

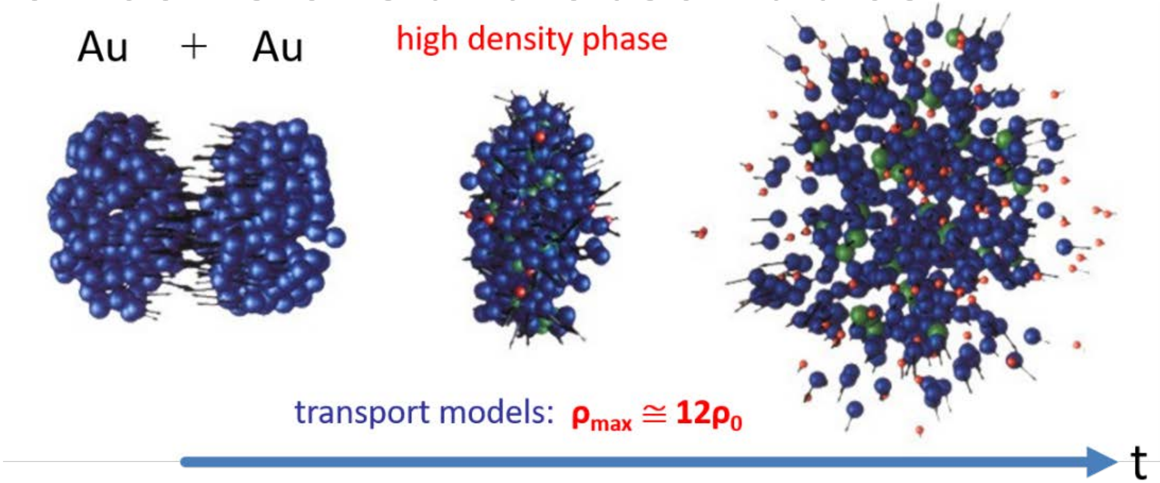
CBM physics cases

- 1) Equation-of-state of QCD matter at neutron star core densities
- 2) Phase transitions from hadronic matter to quarkyonic or partonic matter at high ρ_B, phase coexistence, critical point
- 3) Chiral symmetry restoration in dense baryonic matter
- 4) Extension of the nuclear chart into the strange domain
- 5) Charm production at threshold energies in cold and hot matter

CBM parameters

- High-rate fixed target
- High-energy nucleus-nucleus collisions ($10^5 - 10^7$ Au-Au collisions/s)
- SIS100: ion beam energies between 2 and 14 AGeV, protons up to 29 GeV
- SIS300: ion beam energies up to 45 AGeV, protons up to 90 GeV

Heavy ion collisions and observables

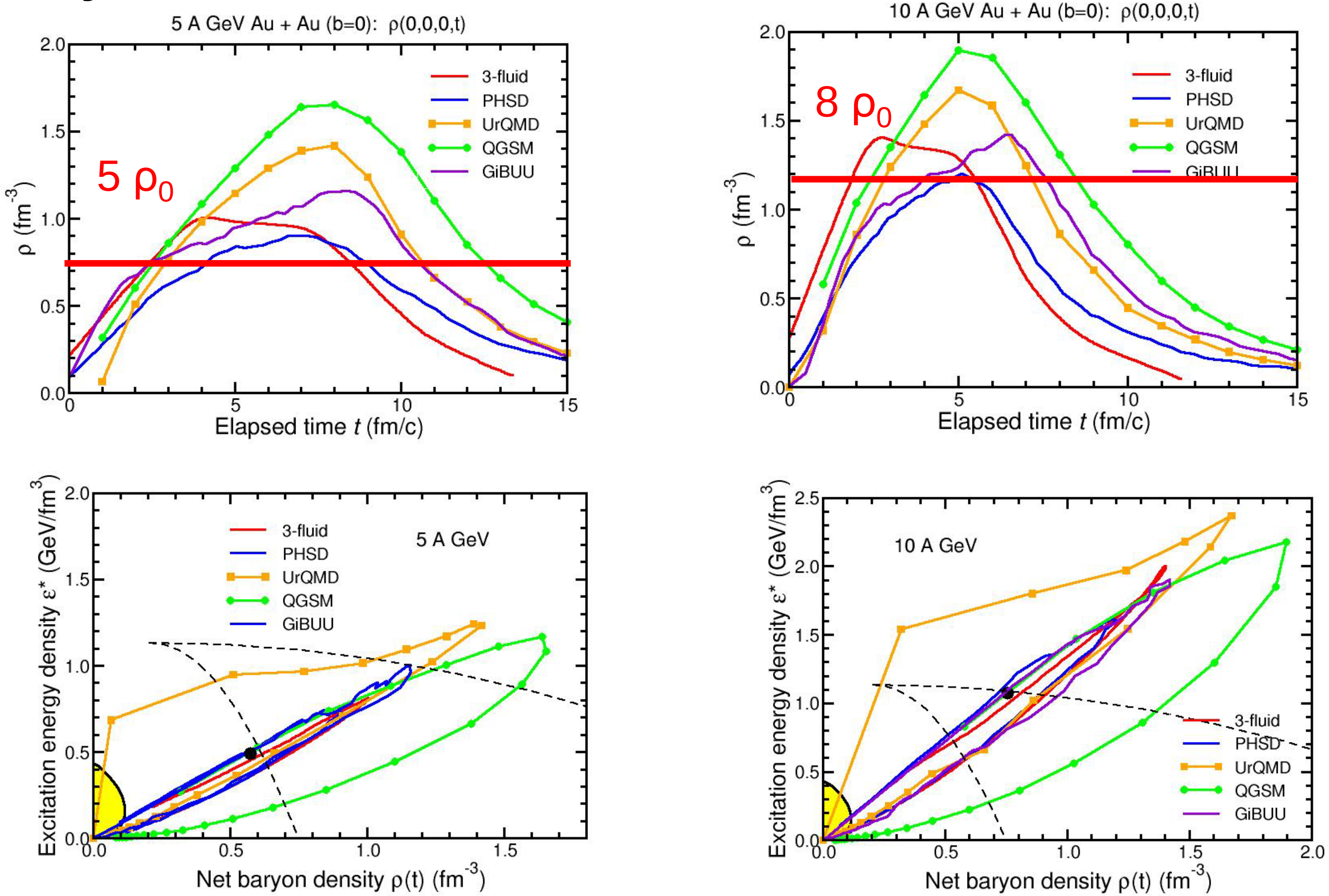


high density and high temperatures reached on a very short time scale:
t ≈ 10^{-22} s (10 fm/c), $\rho = 3.4 \cdot 10^{16}$ g/cm^3, T = 10^{12} K

Rare observables

- low-mass vector mesons by di-lepton pair reconstruction; $\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$
- excitation functions of multi-strange hyperons near expected phase boundary
  - E.g. $\frac{\overline{\Omega}^+}{week} \sim 10^5 @ \sqrt{s_{NN}} = 3.5\ GeV$
- collective flow of identified particles (π,K,p,Λ,Ξ,Ω,...)
- Single and double hyper-nuclei
- excitation function of charm production (J/ψ, D^0, $D^{\pm}$)
- Critical point search using event-by-event fluctuations of conserved quantities (Baryon number, strangeness, charge)

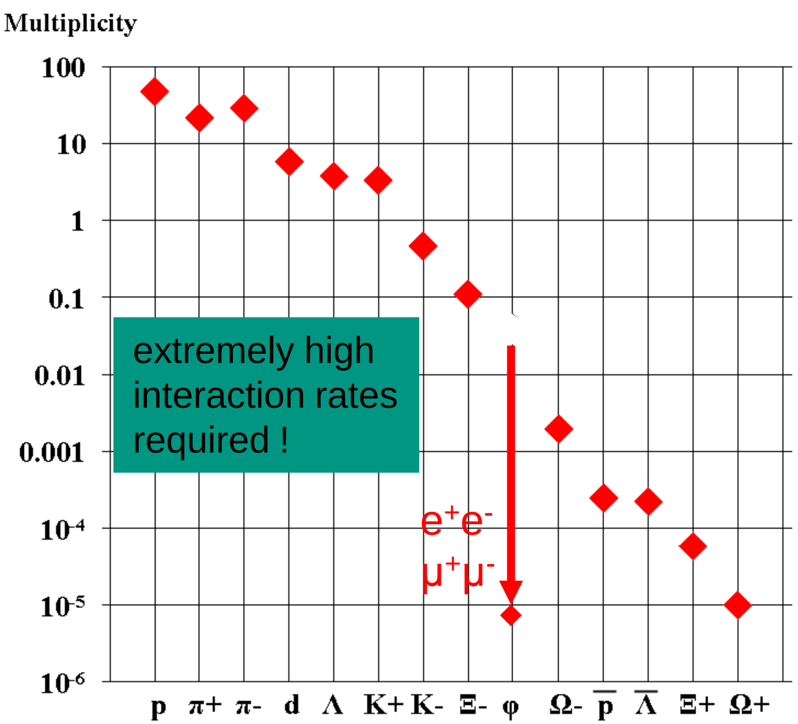
Baryon densities in central Au+Au collisions



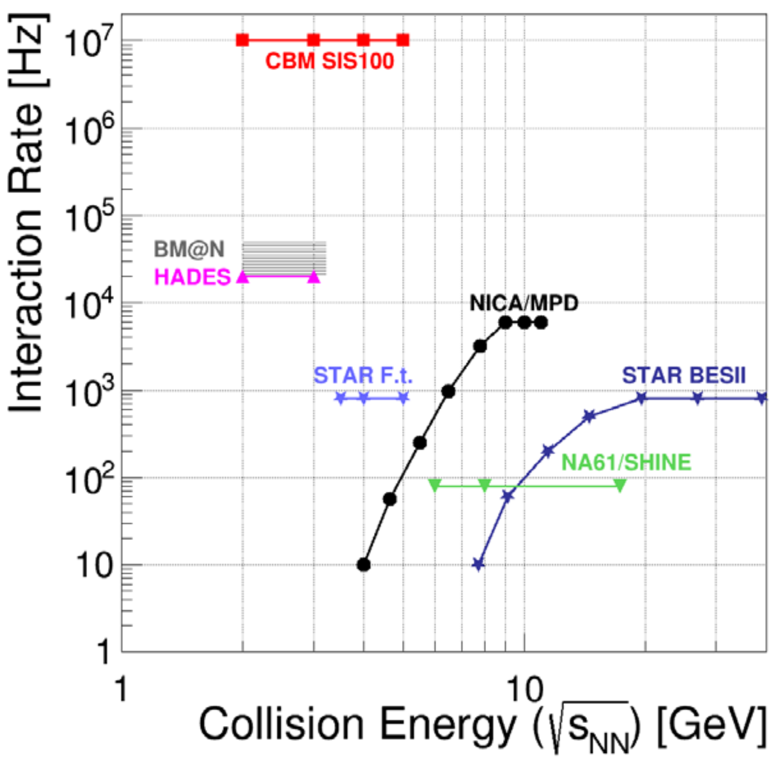
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

Experimental challenges

- Combination of a large-acceptance fast detector and a high-speed data read-out system with high-luminosity beams.
- Rate capability is key feature to measure observables with high precision

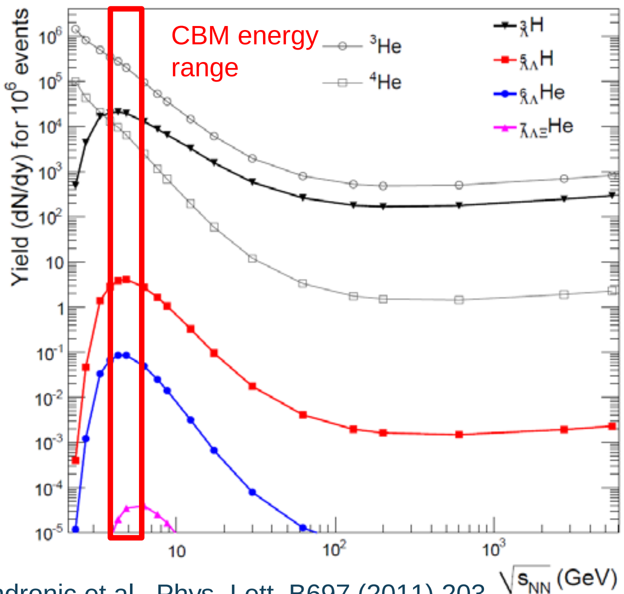


Statistical model, A. Andronic, priv. com.



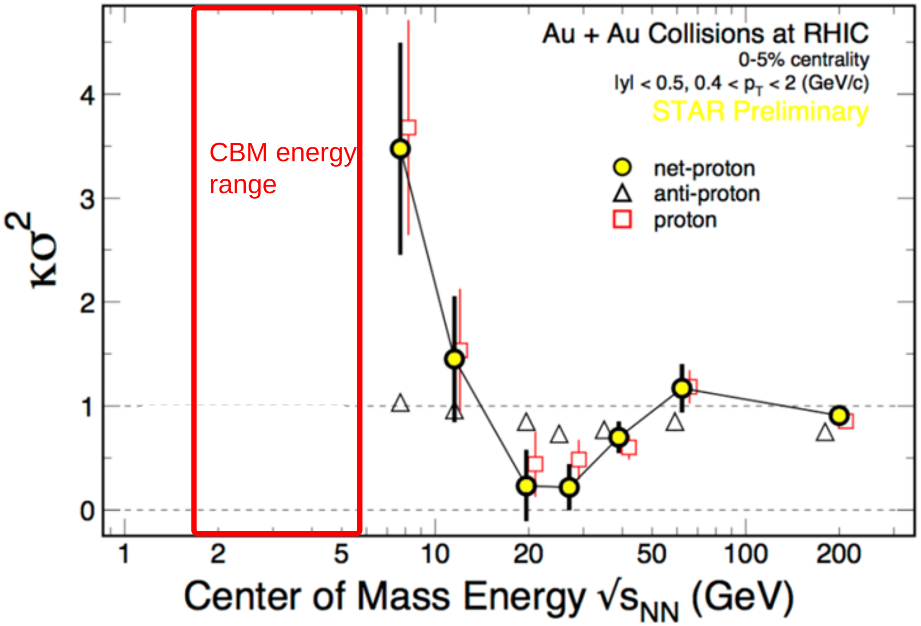
Discovery potential

Hypernuclei yields at midrapidity for central collisions (thermal model)



A. Andronic et al., Phys. Lett. B697 (2011) 203

volume-independent cumulant ratio $\kappa\sigma^2$ of the net-proton multiplicity distribution

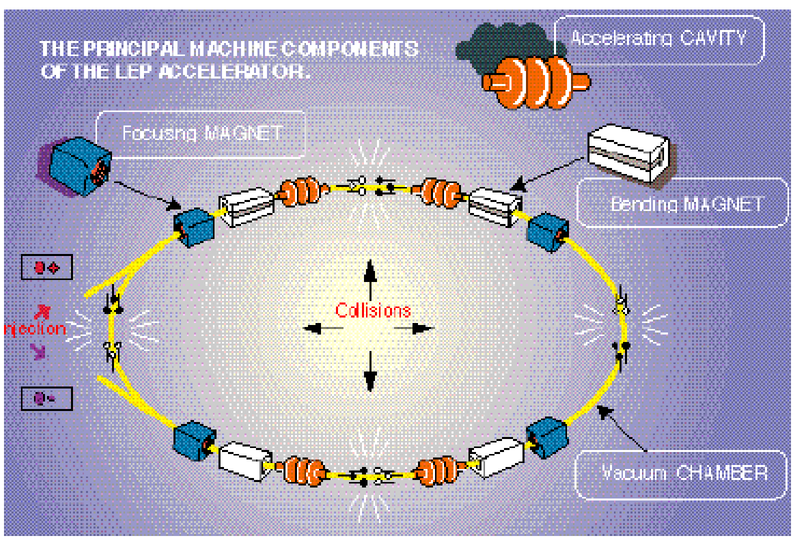


- Maximum in SIS100 energy range
- Hydrogen and helium hypernuclei will be measured in huge amounts
- Discovery potential for light double-Λ hypernuclei

Summary

- model calculations predict the creation of strongly interacting QCD matter at extreme values of density, similar to neutron star core densities.
- opportunity to explore the QCD phase diagram in the region of high net-baryon densities, to study the equation of state, to search for phase transitions, chiral symmetry restoration, and exotic forms of (strange) QCD matter with a dedicated experiment.
- Measurement of the collective behaviour of hadrons, together with rare diagnostic probes such as multi-strange hyperons, charmed particles and vector mesons decaying into lepton pairs with unprecedented precision and statistics
- Reaction rates up to 10MHz requires very fast and radiation hard detectors, a novel data read-out and analysis concept including free streaming front-end electronics.

Collider vs. fixed target experiments



$s_{NN} = (E_1 + E_2)^2 - (\mathbf{p_1} + \mathbf{p_2})^2$

collider:

$\mathbf{p_1} + \mathbf{p_2} = 0 \quad \rightarrow \sqrt{s_{NN}} = E_1 + E_2$

fixed target: $E_2 = m$, $\mathbf{p_2} = 0$

$s_{NN} = (E_{kin} + 2m)^2 - \mathbf{p_1}^2$

$s_{NN} = 2m \cdot (E_{kin} + 2m)$

for $E_{kin} \gg m$: $\sqrt{s_{NN}} = 1.4 \cdot \sqrt{E_{kin}}$