Compressed Baryonic Matter Experiment

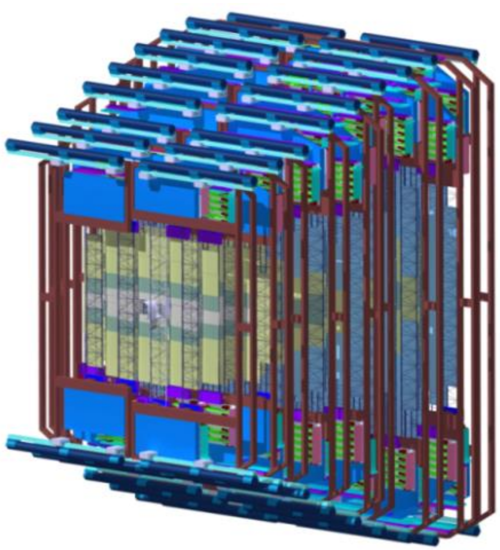
HIC for FAIR
Helmholtz International Center

FAIR

GSI

The Silicon Tracking System of the CBM experiment

Tomas Balog
on behalf of the CBM collaboration



- FAIR overview
- preview of CBM experiment
- STS requirements and detector concept
  - system performance
  - prototype components
  - in-beam and laboratory tests
  - system integration

DESY, Hamburg, 14.11.2014

Accelerator Facility

Primary Beams

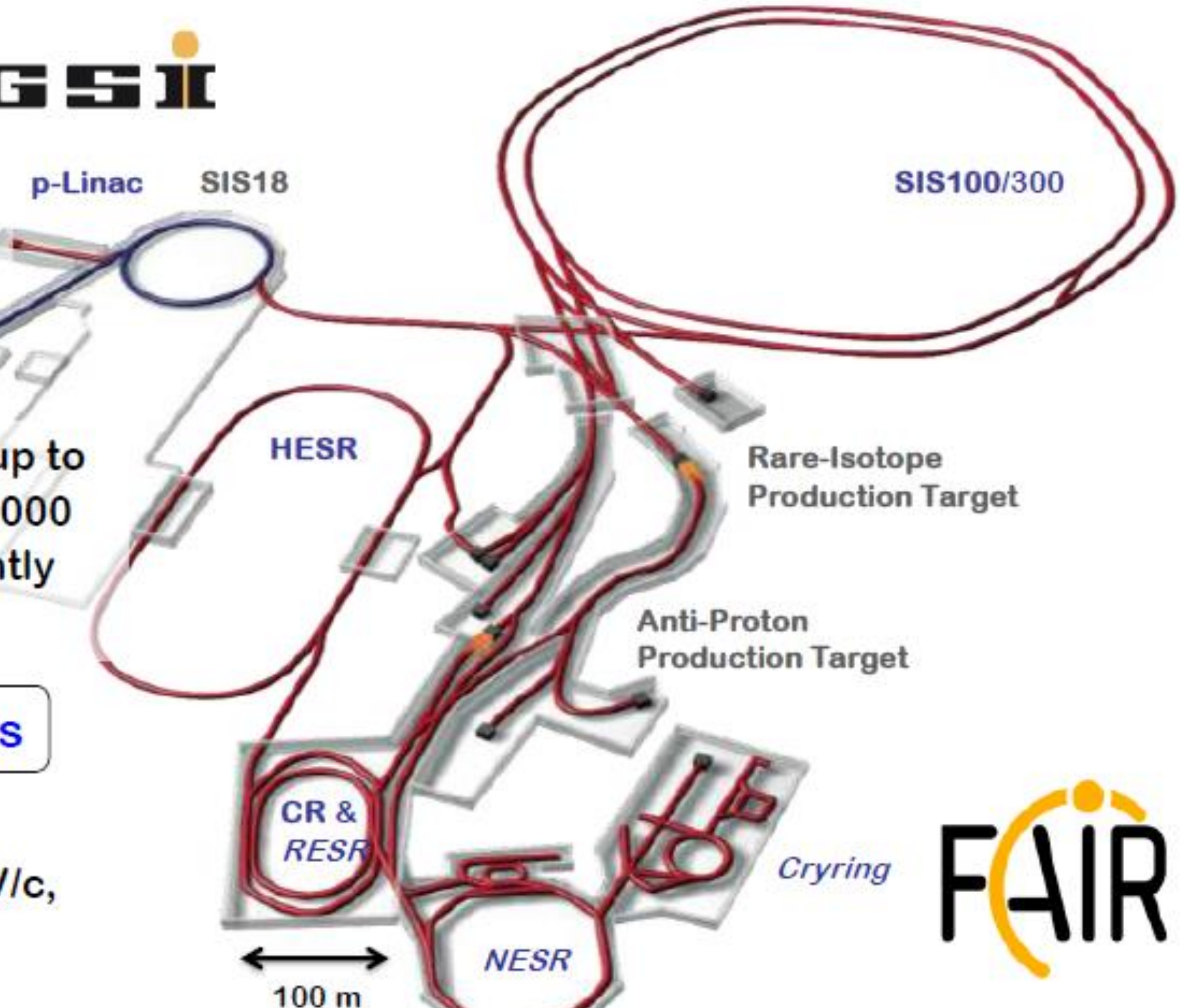
- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3×10^{13}/s 30 GeV protons

Secondary Beams

- range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Storage and Cooler Rings

- radioactive beams
- 10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled



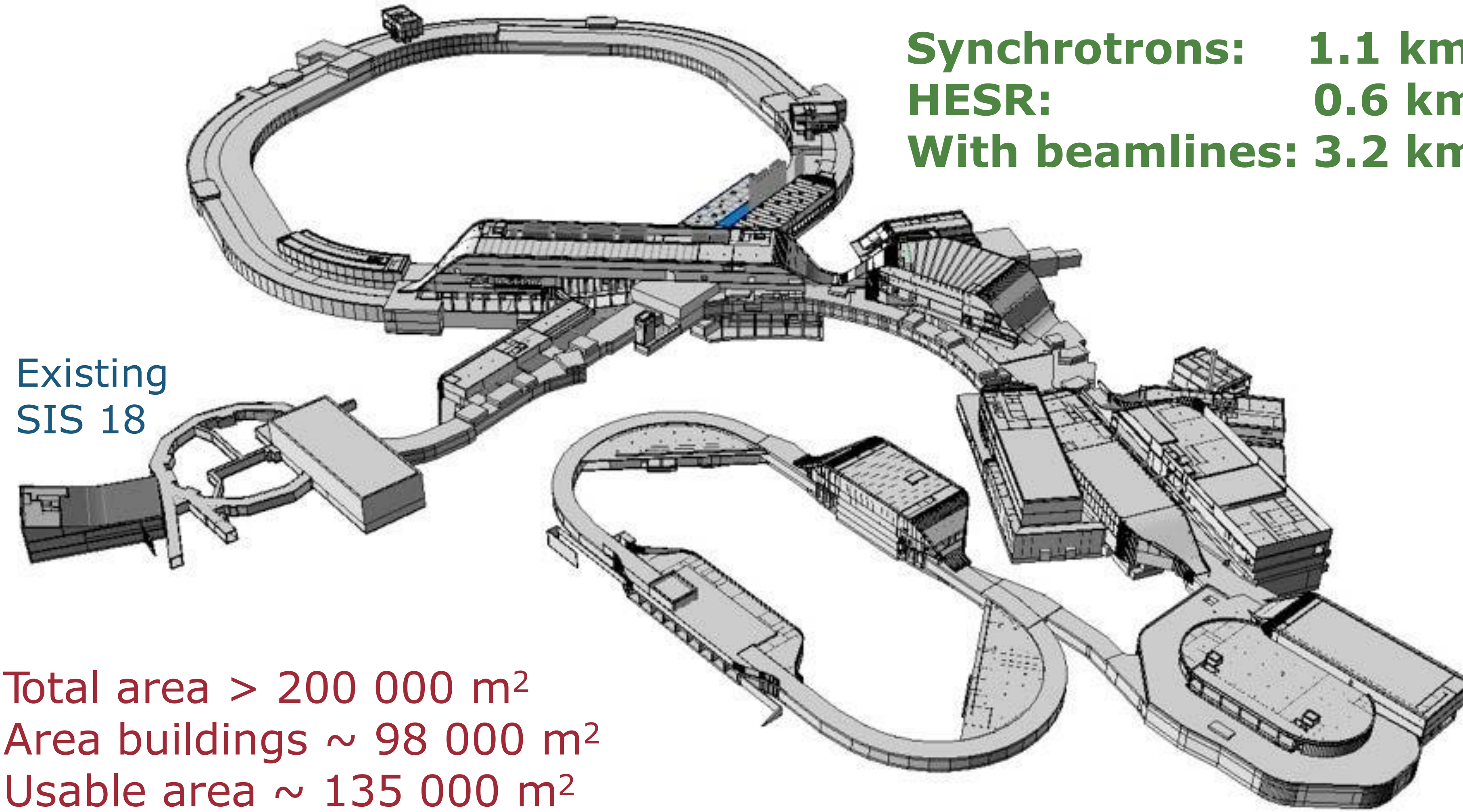
Technical Challenges

- cooled beams, rapid cycling superconducting magnets

Civil construction is presently the lead process

FAIR accelerator complex

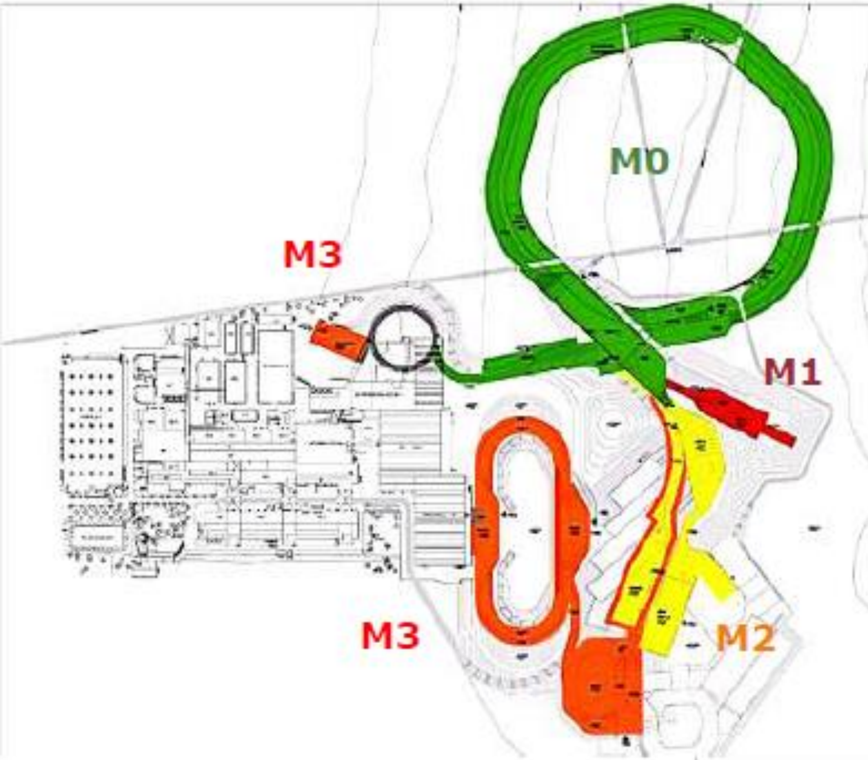
Synchrotrons: 1.1 km
HESR: 0.6 km
With beamlines: 3.2 km



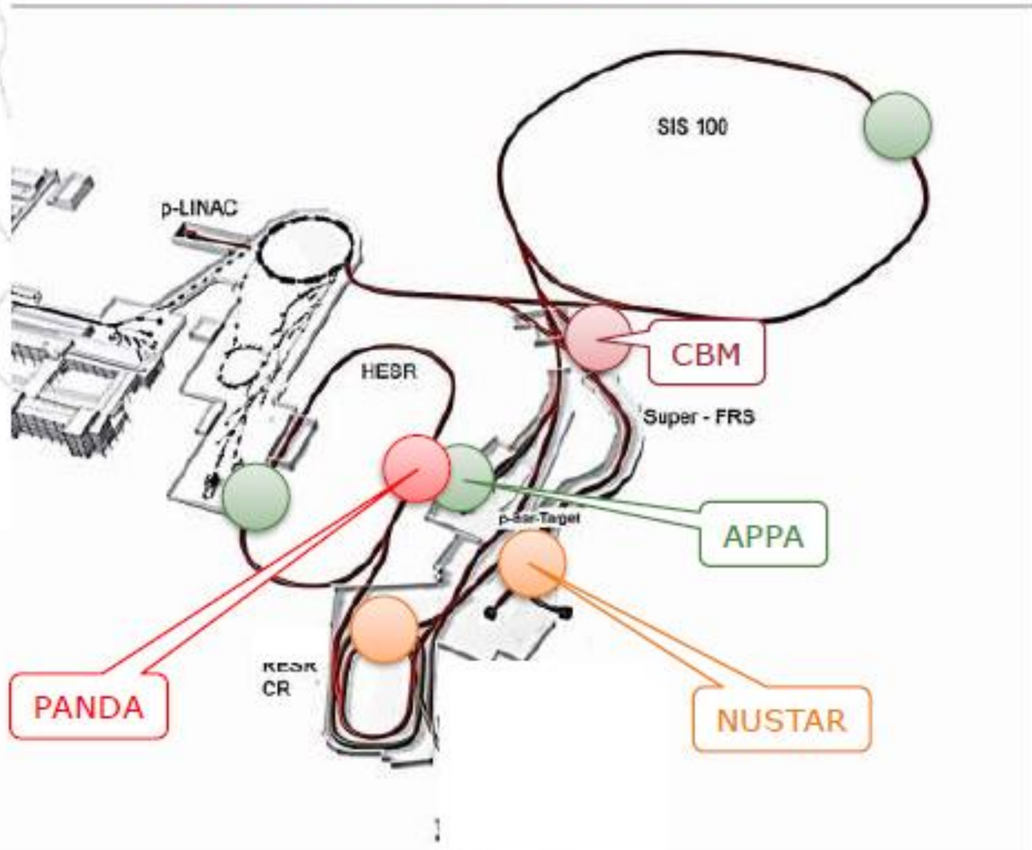
Total area > 200 000 m²
Area buildings ~ 98 000 m²
Usable area ~ 135 000 m²
Volume of buildings ~ 1 049 000 m³
Substructure:~ 1500 pillars, up to 65 m deep

The FAIR Project

FAIR Modularised Start Version



Science with the MSV



Experiments

M0: SIS100

M1: CBM,APPA

M2: NUSTAR

M3: PANDA, APPA, NUSTAR

The MSV should enable realization of outstanding forefront research program to all 4 scientific pillars of FAIR

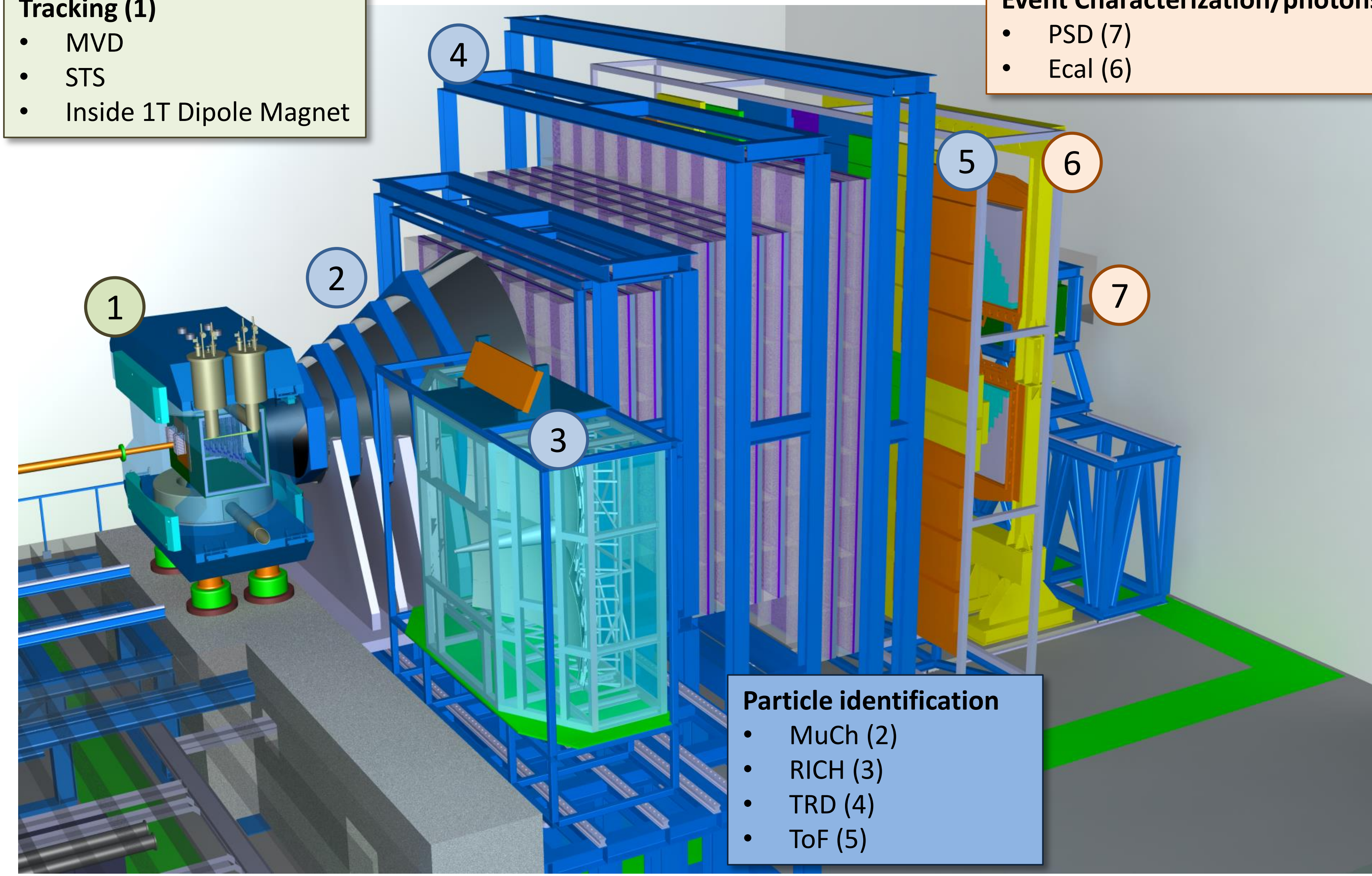
CBM building

Compressed Baryonic Matter experiment

- high-rate fixed target experiment (up to 10 MHz)
- electron and muon configuration to cross-check the systematics

Tracking (1)
- MVD
- STS
- Inside 1T Dipole Magnet

Event Characterization/photons:
- PSD (7)
- Ecal (6)

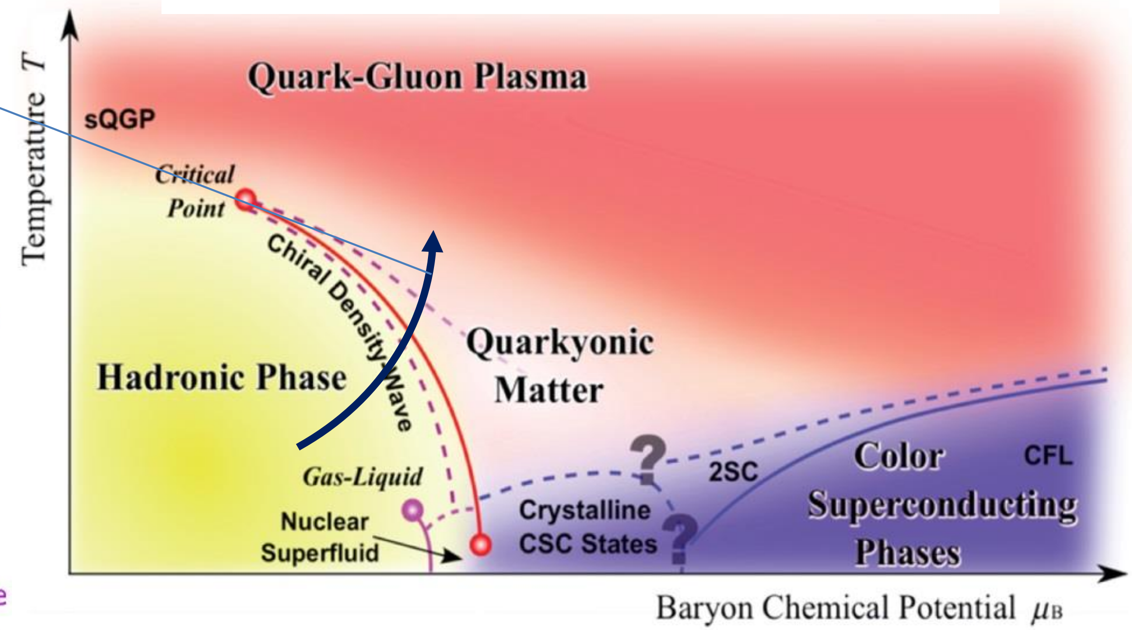


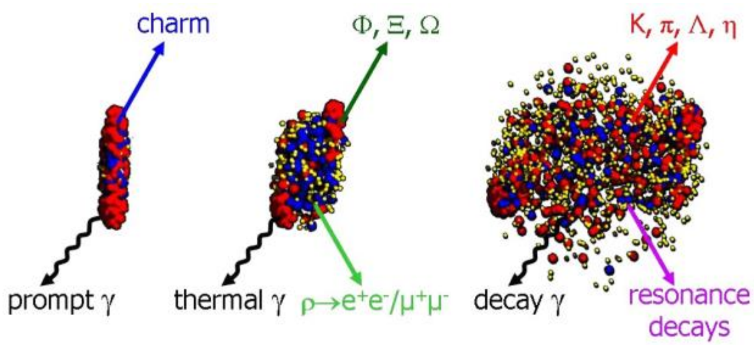
Particle identification
- MuCh (2)
- RICH (3)
- TRD (4)
- ToF (5)

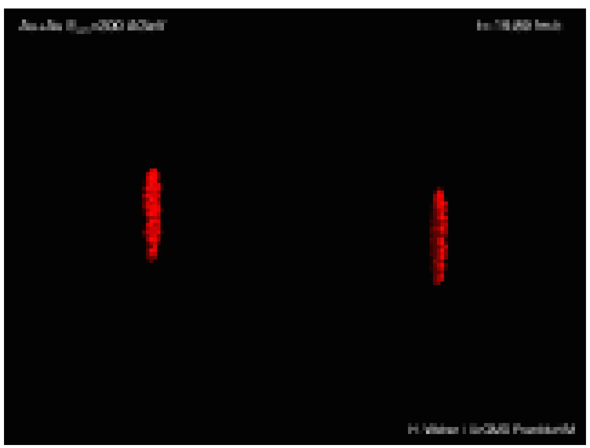
Physics cases in CBM

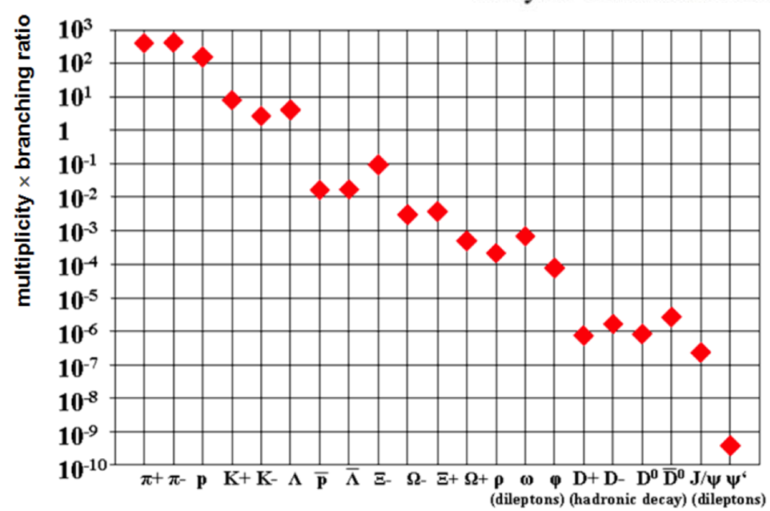
- highest net-baryon densities
  - processes in neutron stars
- rare observables created during early stages of fireball
- first order phase transition?

$$E/A = \sqrt{(0.3 \times B \times r \times Z/A)^2 + m^2} - m$$









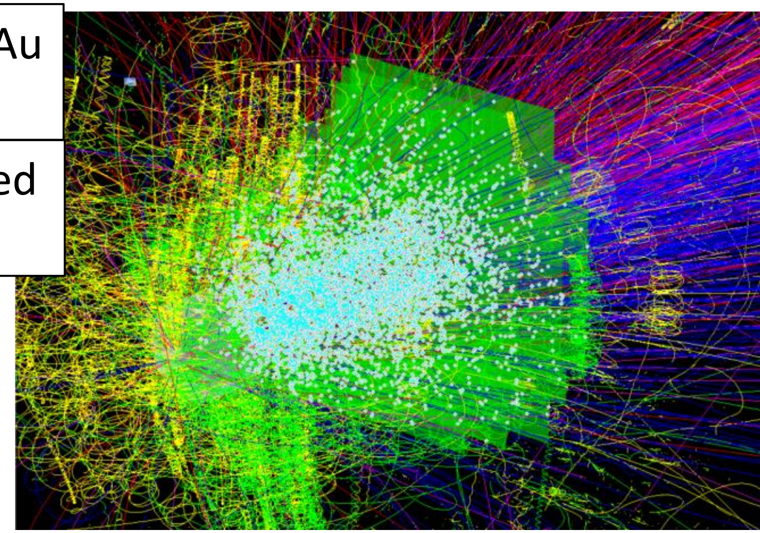
Experimental requirements

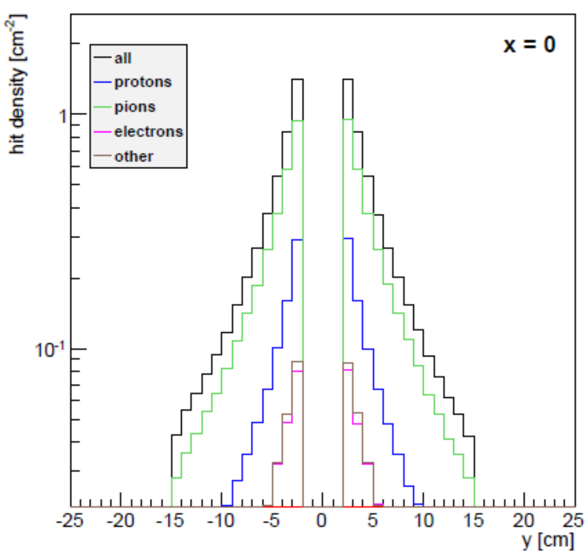
- 10^5 - 10^7 Au+Au reactions/sec
- determination of displaced vertices ($\sigma \approx 50\ \mu m$)
- identification of leptons and hadrons
- fast and radiation hard detectors
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

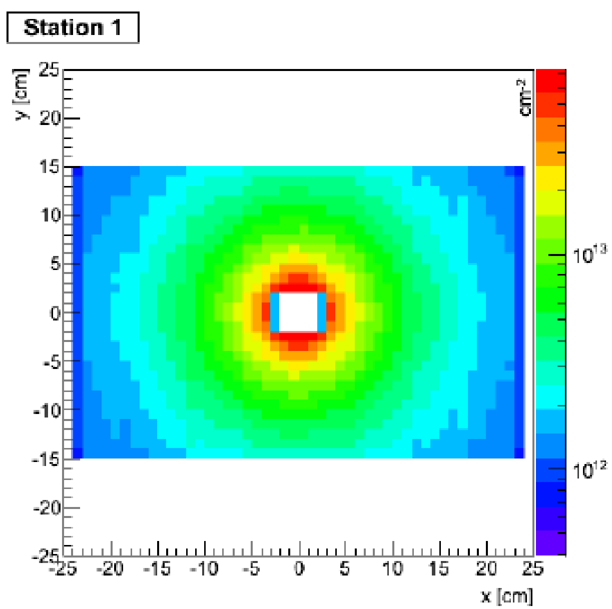
Tracking nuclear collisions at SIS-300 and at SIS-100

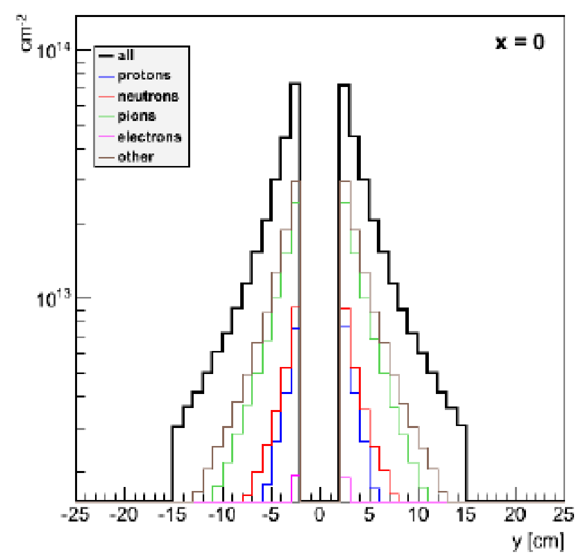
- **CBM: high-rate experiment**
  10^5 - 10^7 interactions/sec
- **hit rates up to 20 MHz/cm²**
- **radiation hard sensors**
  compatible with the CBM physics program
  – 1×10^{13} n_{eq}/cm^2 (SIS100)
  – 1×10^{14} n_{eq}/cm^2 (SIS300)

central Au+Au 25 AGeV
~700 charged particles



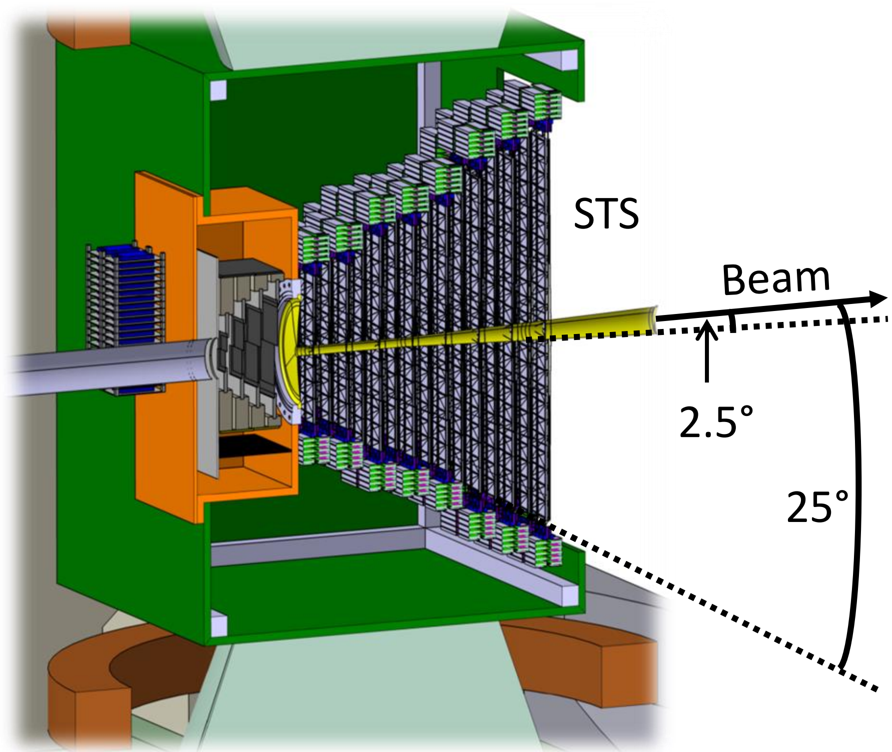






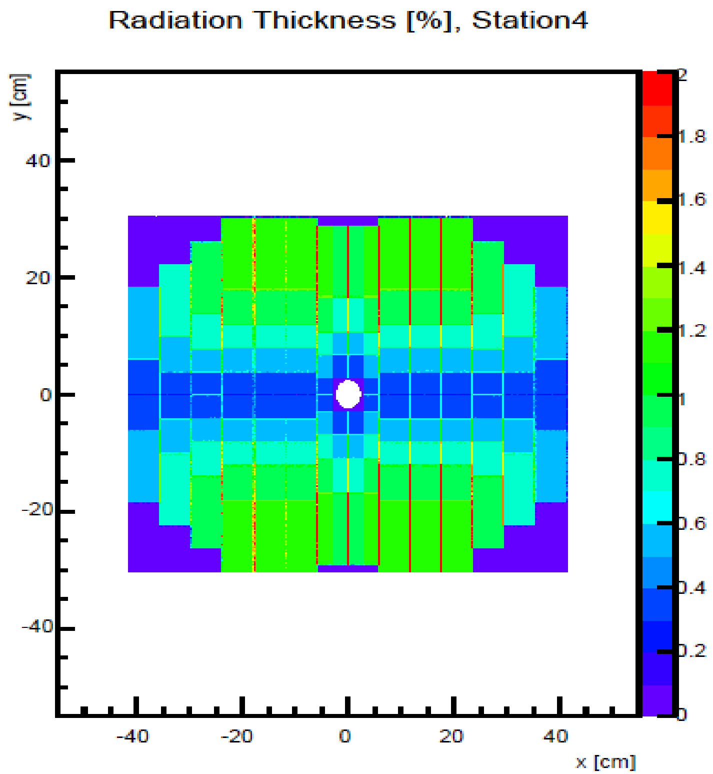
Tracking nuclear collisions at SIS-300 and at SIS-100

- **coverage**
  - rapidities from center-of mass to close to beam
  - aperture 2.5° < Θ < 25°
- **low mass** large-area detector
  - high-resolution momentum determination
  - track matching into MVD and RICH/MUCH
- **momentum resolution**
  - δp/p ≅ 1%
  - field integral 1 Tm
  - 25 μm single-hit spatial resolution
  - material budget per station ~1% X_0
- **efficient hit & track reconstruction**
  - close to 100% hit and tracking eff.
- **read-out**
  - self-triggering read-out
  - signal shaping time < 20 ns
  - no pile-up

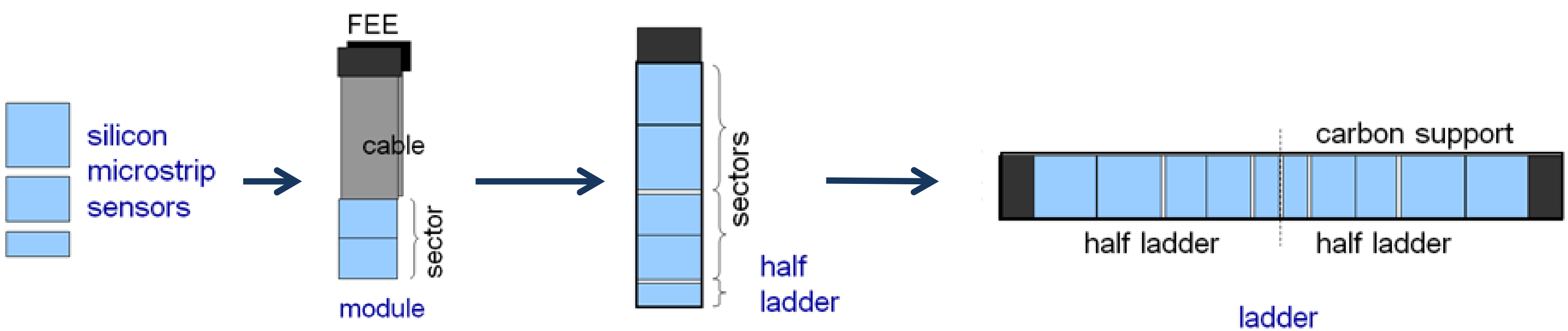


- fast free-streaming readout
- online event selection

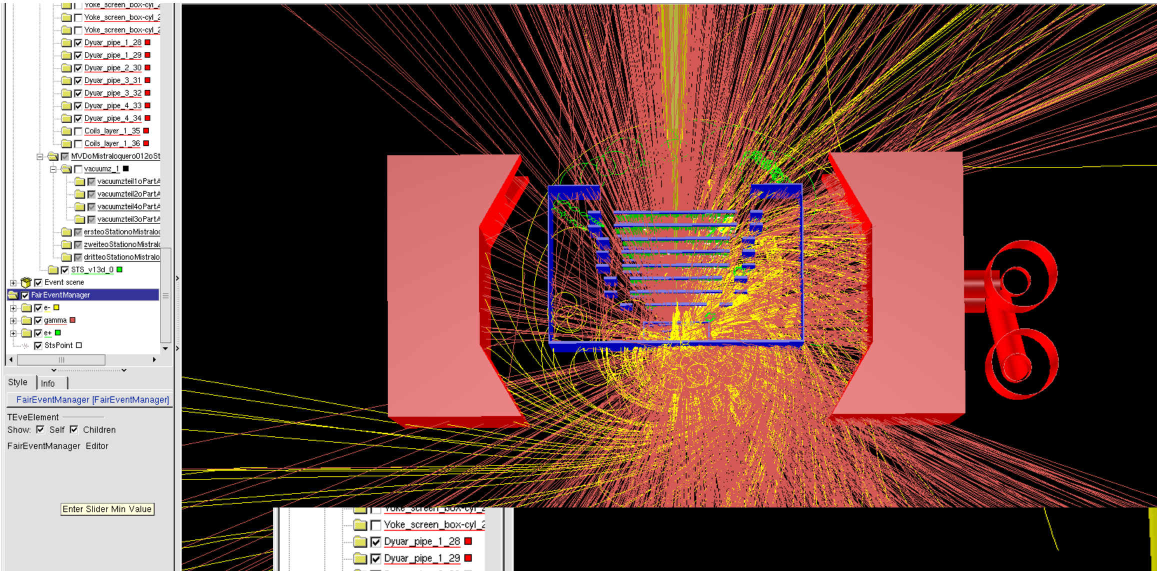
STS concept



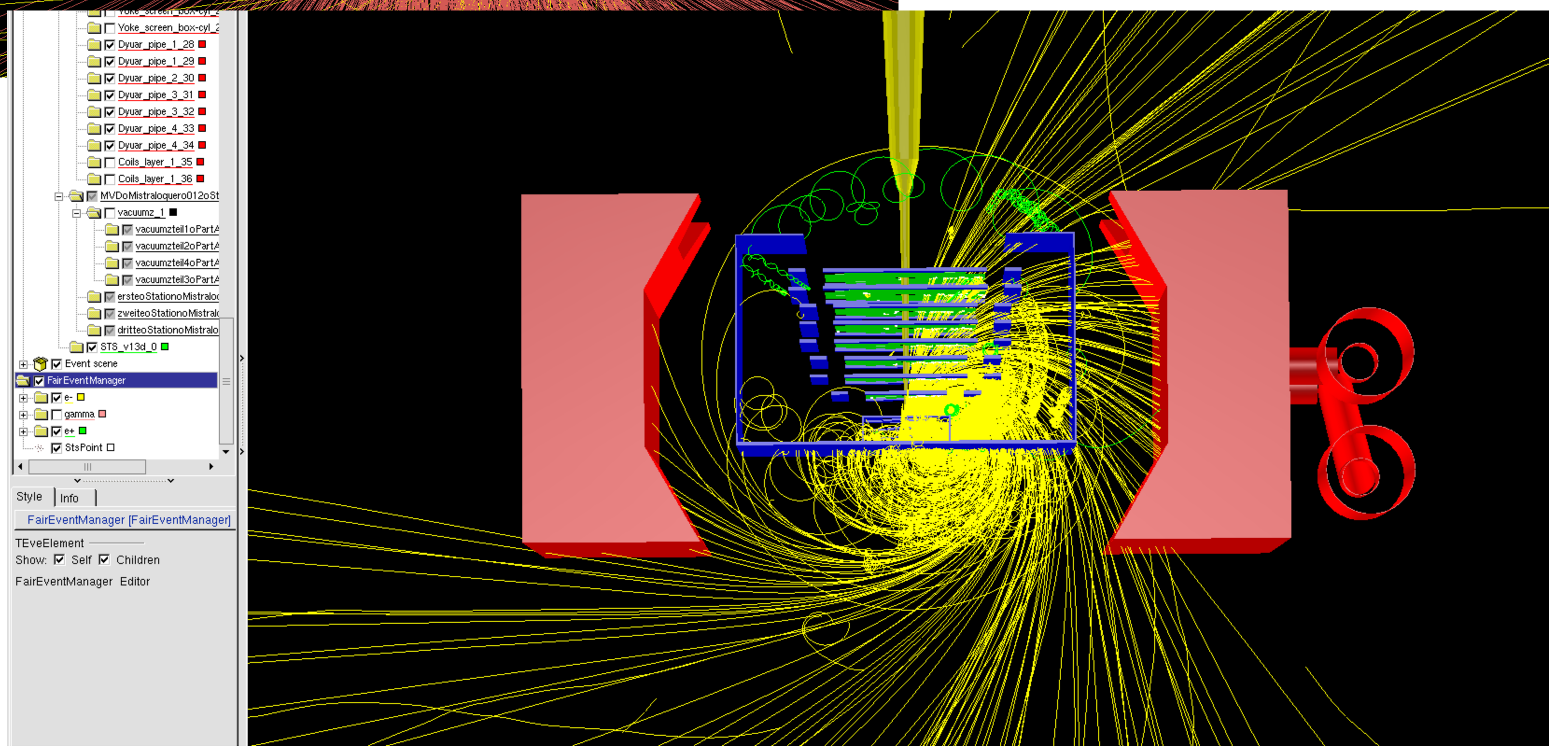
- 8 tracking stations between 0.3 m and 1 m downstream the target.
- Built from double-sided silicon micro-strip sensors in 3 sizes, arranged in modules on a small number of different detector ladders.
- Readout electronics outside of the physics aperture.



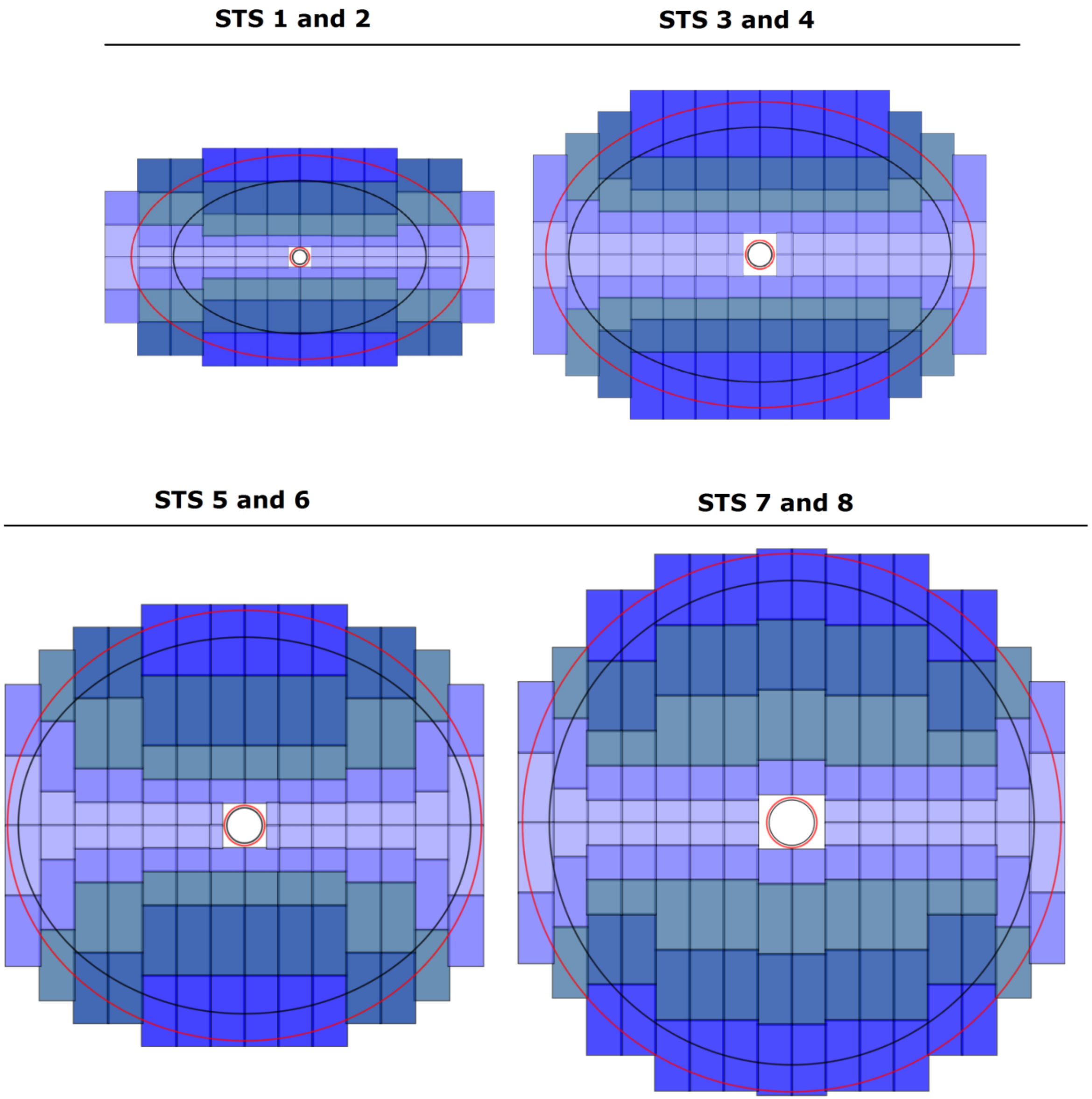
Delta electrons



Interaction rate – 10^9 (every 1 ns)
- 1% interaction target thus
100x More interactions
for delta electrons

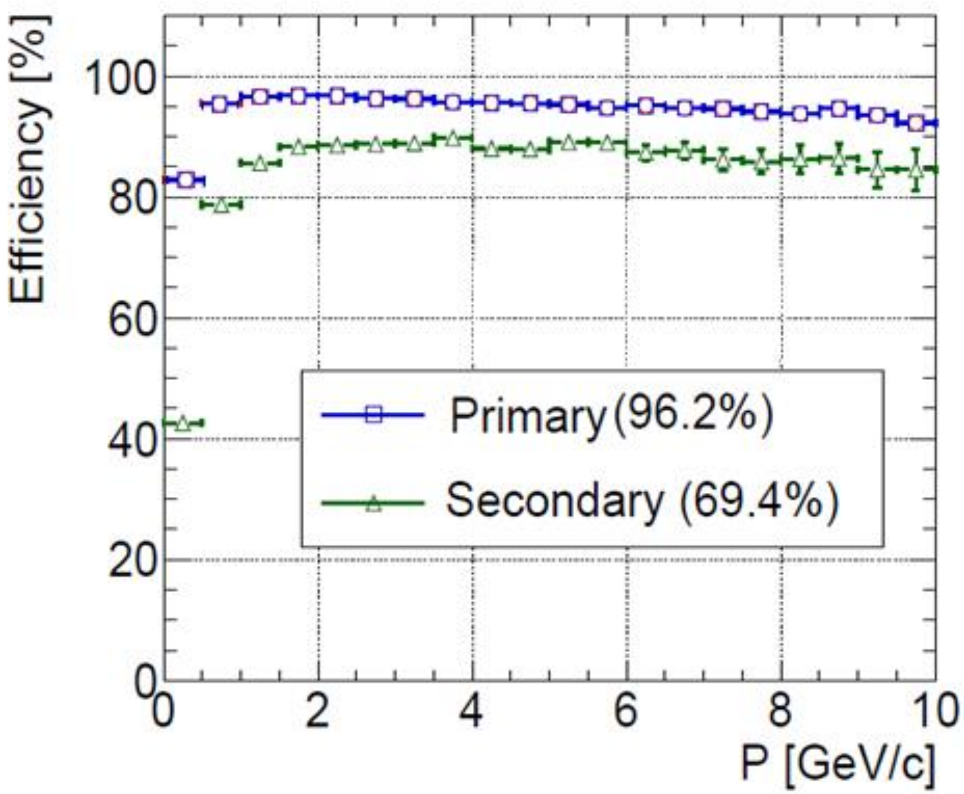


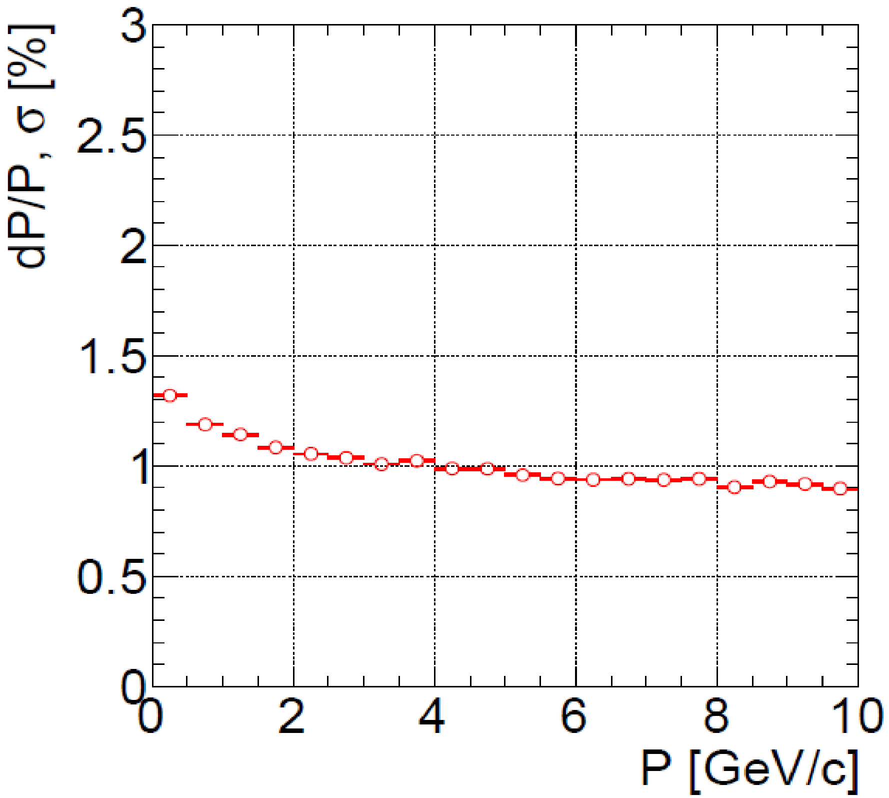
STS layout



- Stations arranged in 4 duplets
- Minimizing amount of modules
- Strips lengths – 2 cm, 4 cm, 6 cm and in case of daisy chained sensors 12 cm
- Granularity according to the hit densities
- Components breakdown:
  - ✓ 106 ladders (17 types)
  - ✓ 896 modules
  - ✓ 1220 sensors
  - ✓ 14144 chips
  - ✓ 1.8 Mio channels

STS performance



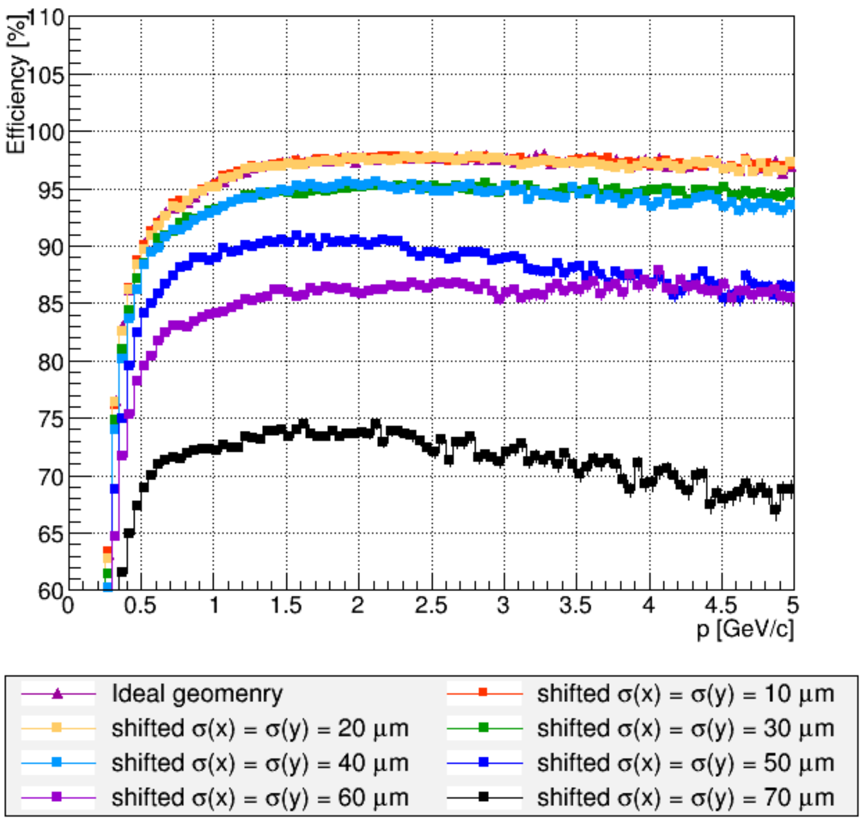


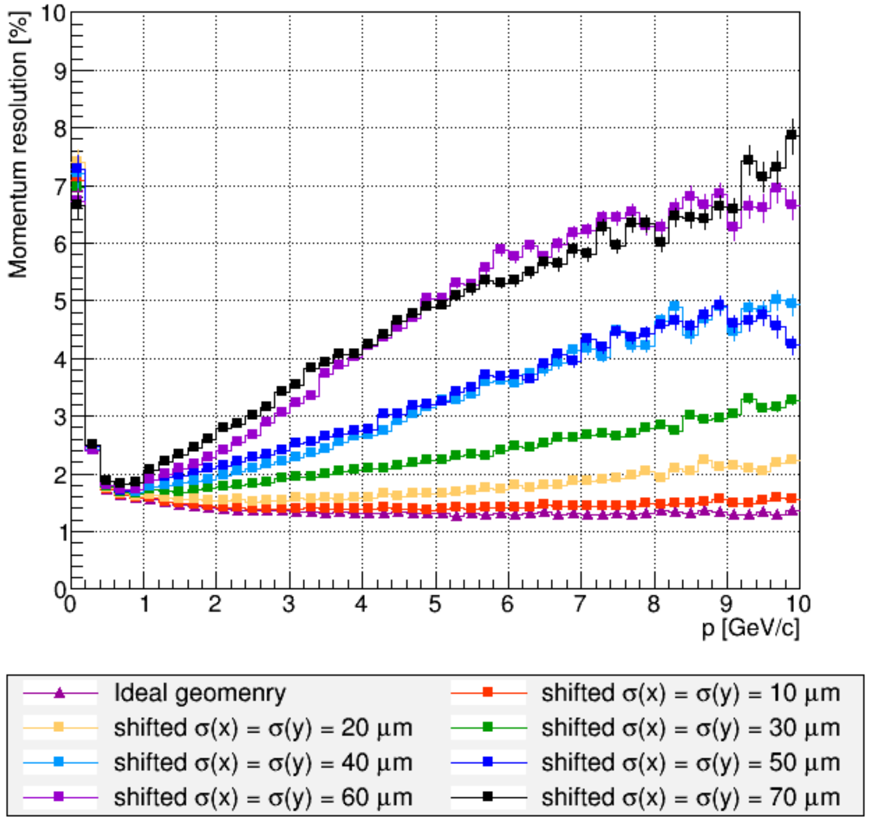
Efficiency ≈ 96%

Momentum resolution ≈ 1 %

Misalignment studies

- Efficiency and momentum resolution as a function of modules misplacement
- Misplacements according to the Gaussian distribution

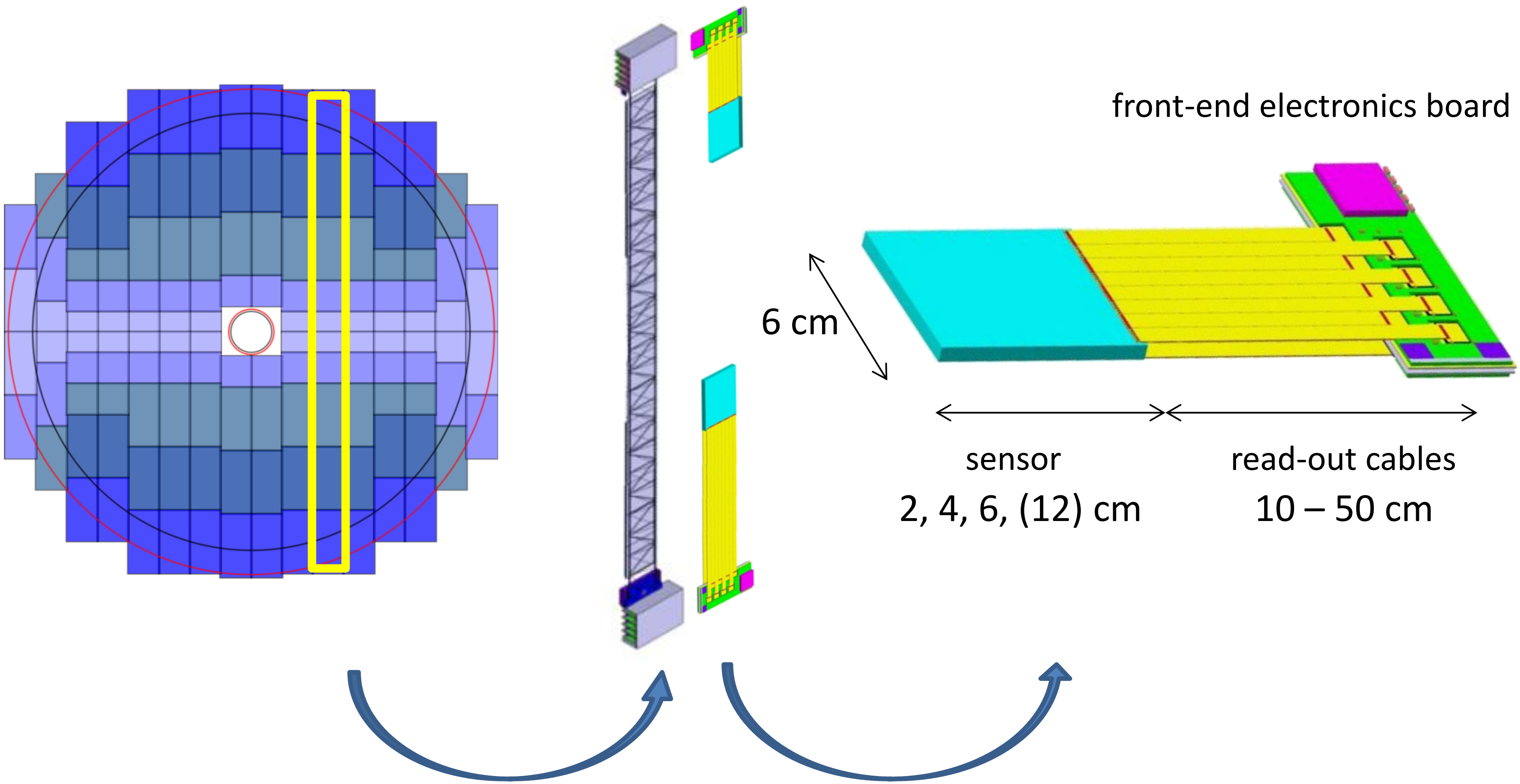




- For the STS tracker unknown misalignment up to 20 μm is allowed

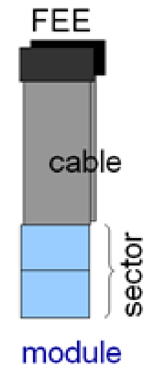
STS module

module := building block of ladders smallest assembled functional unit



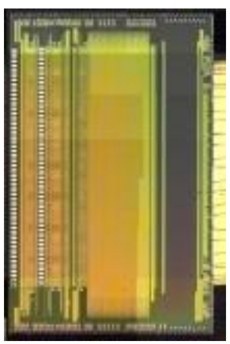
STS module

- High-density silicon detector module
- Procedures for module assembly + integration
- Exploration of technologies for mass-production

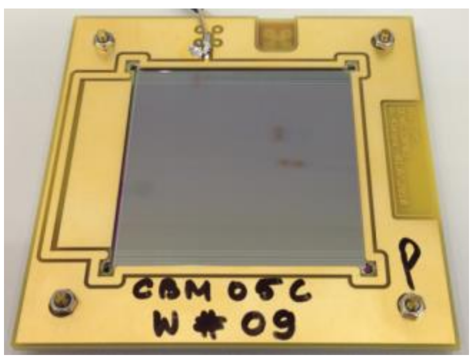


Components:

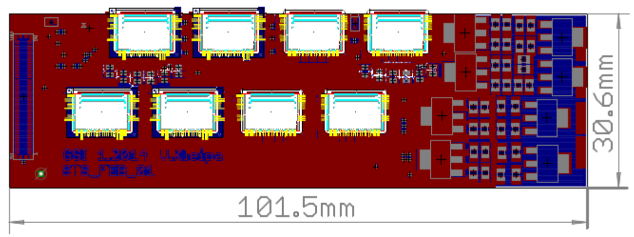
ASICs

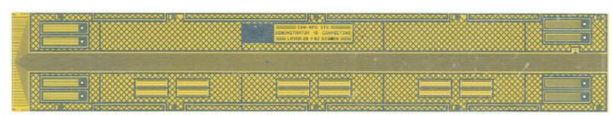


sensors



FEB



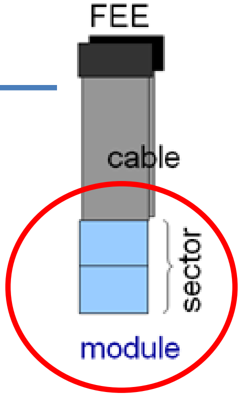


readout cables

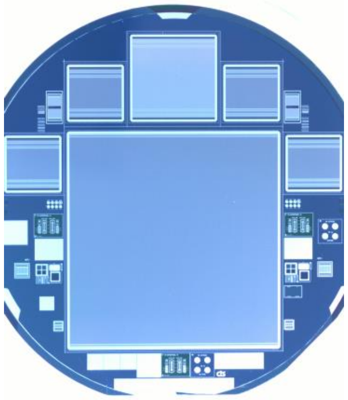
module assembly study

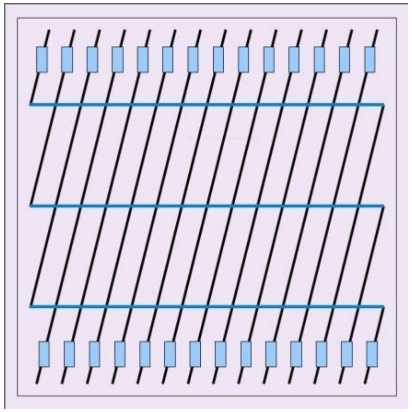
EU-FP7 HadronPhysics3 – *Work Package ULISINT*
http://www.hadronphysics3.eu/

Micro-strip silicon sensors

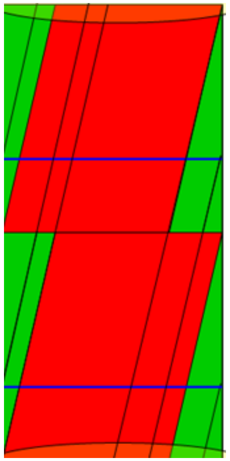


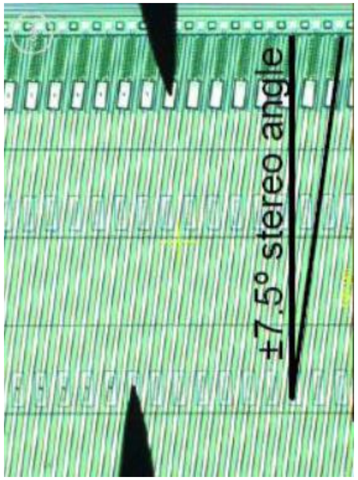
- 300 µm thick, n-type silicon
- double-sided segmentation
- 1024 strips of 58 µm pitch
- strip length 6.2/4.2/2.2 cm
- angle front/back: 7.5 deg
- read-out from top edge
- rad. tol. up to 10^{14} n_{eq}/cm^2

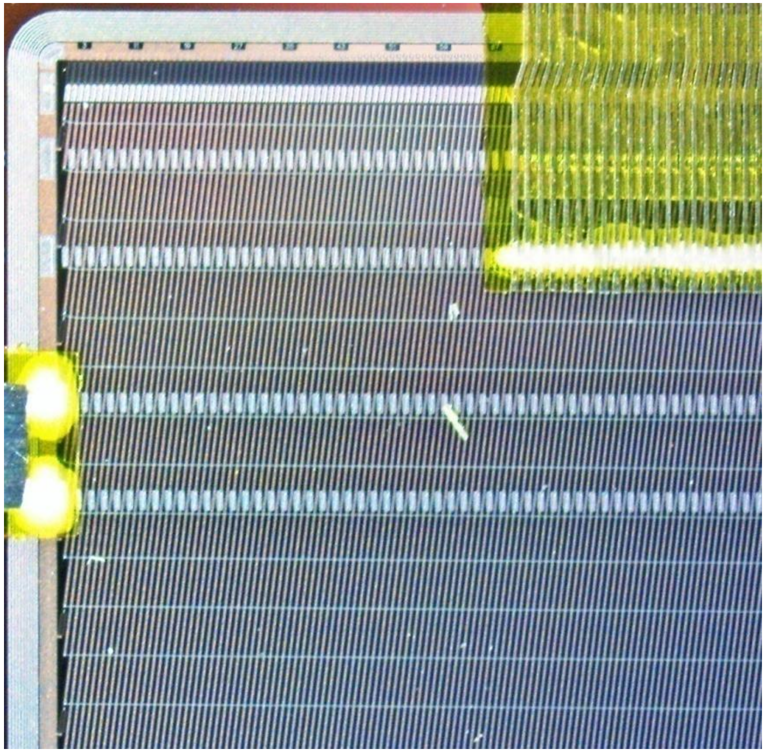




Strips reaching the border are continued on the other side
$\Rightarrow$ Needs double metal layer or external cable

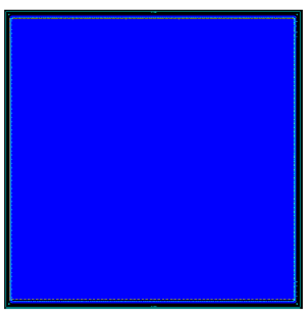




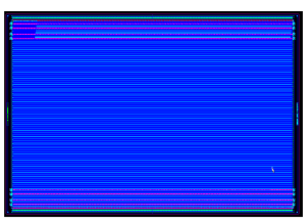


Prototypes of STS micro-strip silicon sensors

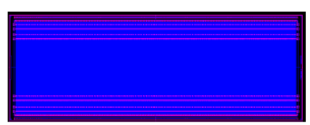
Prototype	Year	Vendor	Processing	Metallization	Size [cm²]	Description
CBM01	2007	CiS	double-sided		5.5 × 5.5	±7.5 deg
CBM03	2010	CiS	double-sided		6 × 6	±7.5 deg
CBM03’	2011	CiS	single/CBM03		6 × 6	test for CBM05
CBM05	**2013**	**CiS**	**double-sided**		**6 × 6**	**7.5/0 deg**
CBM05H4	**2013**	**Hamamatsu**	**double-sided**	**double/single**	**6 × 4**	**7.5/0 deg**
CBM05H2	**2013**	**Hamamatsu**	**single-sided**	**single metal**	**6 × 2**	**7.5/0 deg**
CBM06H6	**2014**	**Hamamatsu**	**double-sided**	**double/single**	**6 × 6**	**7.5/0 deg**
CBM06C6	**2014**	**CiS**	**double-sided**	**single metal**	**6 x 6**	**7.5/0 deg**
CBM66	**2015**	**CiS**	**double-sided**	**single/double**	**6 x 12**	**7.5/0 deg**



CBM05



CBM05H4

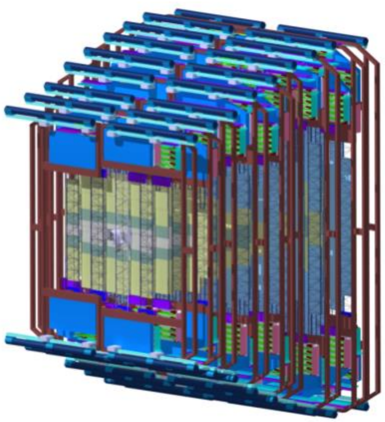


CBM05H2

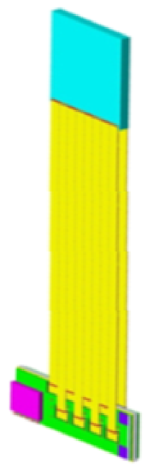
under study: replacement for integrated 2nd metal layer

external on-sensor cable

STS micro-strip silicon sensors

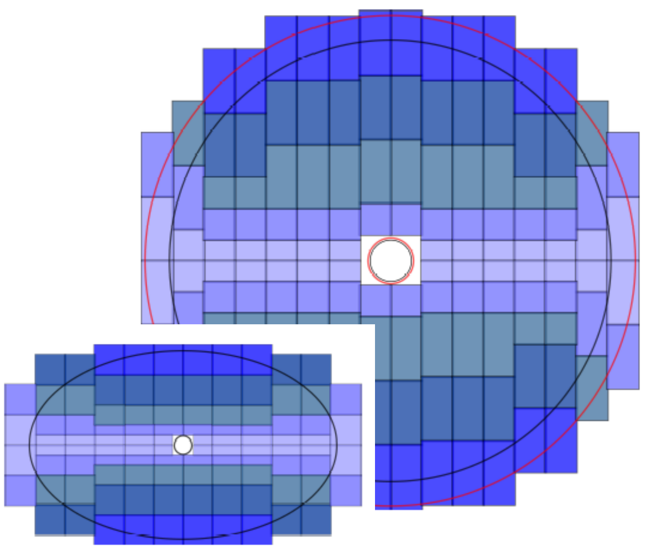


8 tracking stations

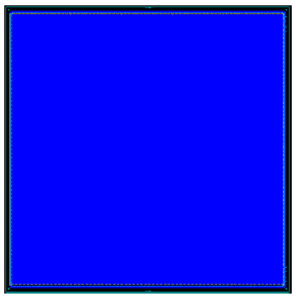


896 modules

106 ladders

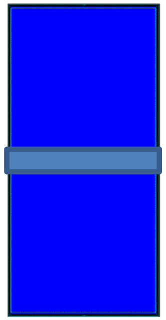


1220 sensors:

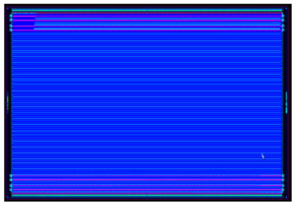


6.2 cm × 6.2 cm

252 single
324 daisy-chains

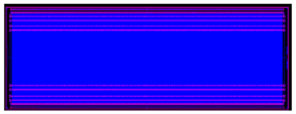


900



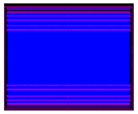
6.2 cm × 4.2 cm

260



6.2 cm × 2.2 cm

60



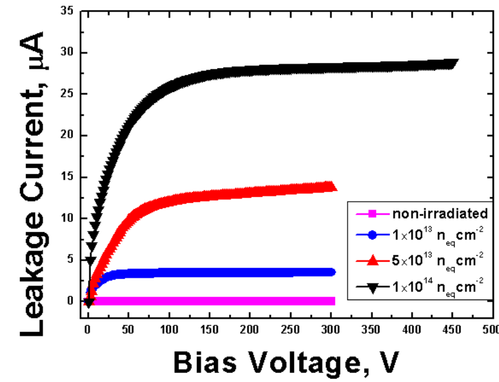
+ small number of “half” sensors

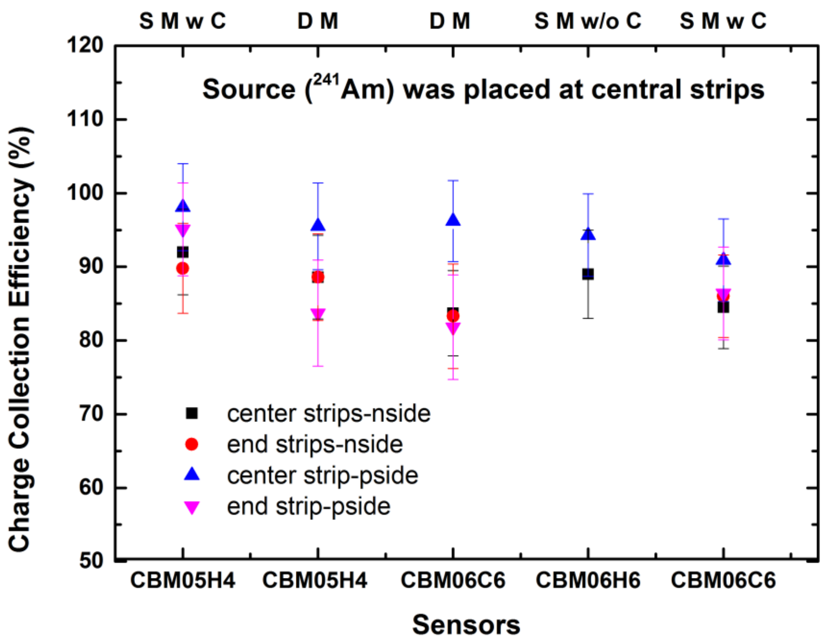
Tests of micro-strip silicon sensors

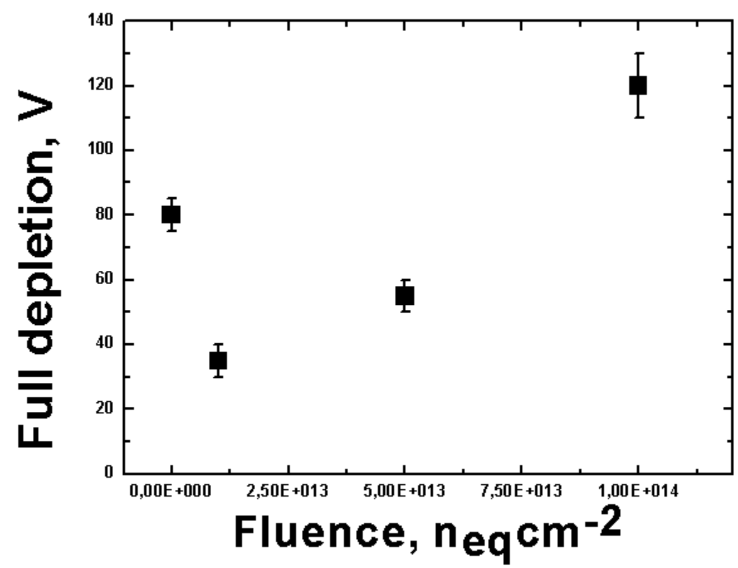
sensor material behaves as expected:

- type inversion at ~ 3 x 10^{13} n/cm^2
- depletion voltage and detector currents change with irradiation and annealing time such that ...
- charge collection OK (γ sources) within “lifetime” fluence

operation at T = -5 °C



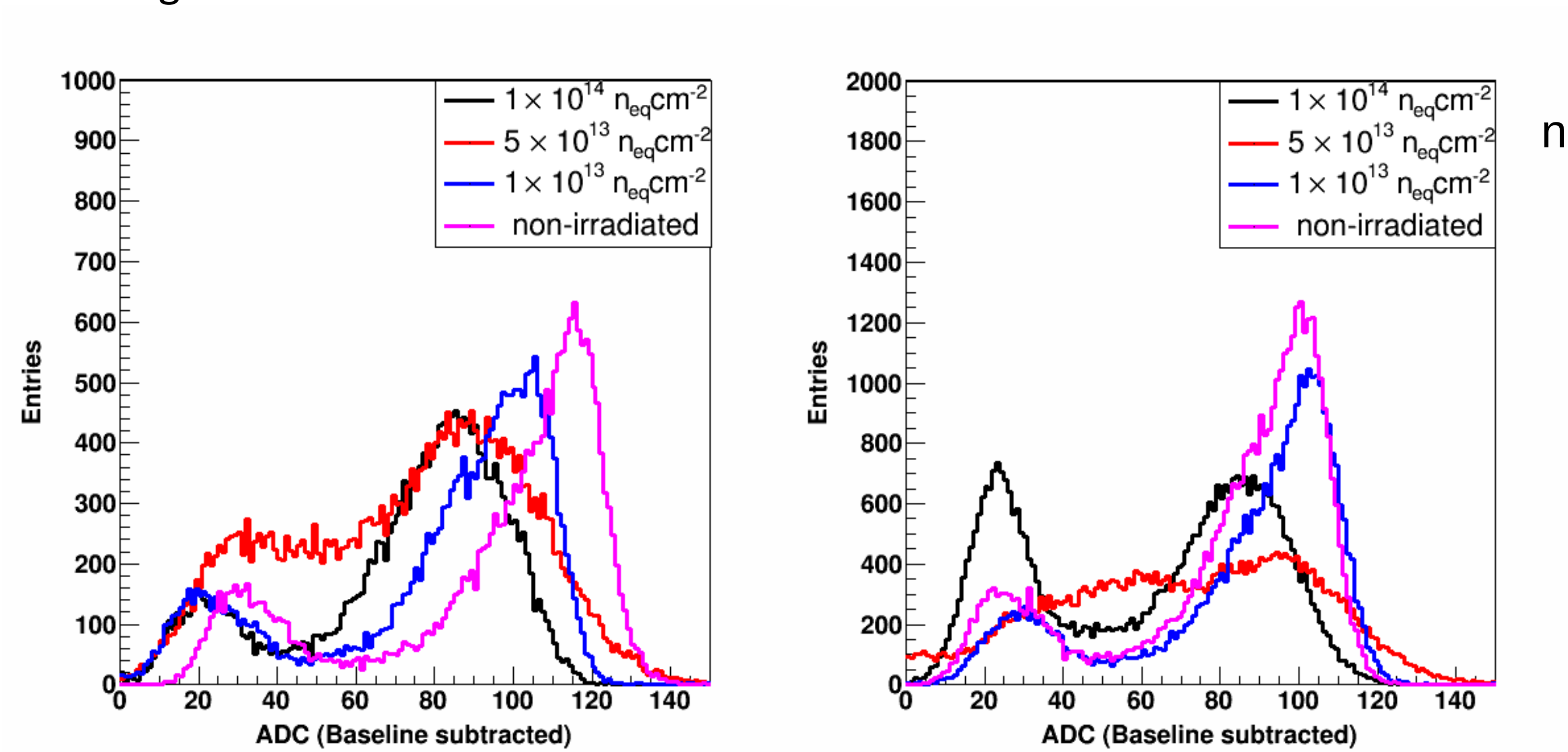




Source tests of the latest silicon sensor prototype CBM05

- ADC spectrum, ^{241}Am gamma source
- expected signal at 117 ADC - 16.5 ke-

p side

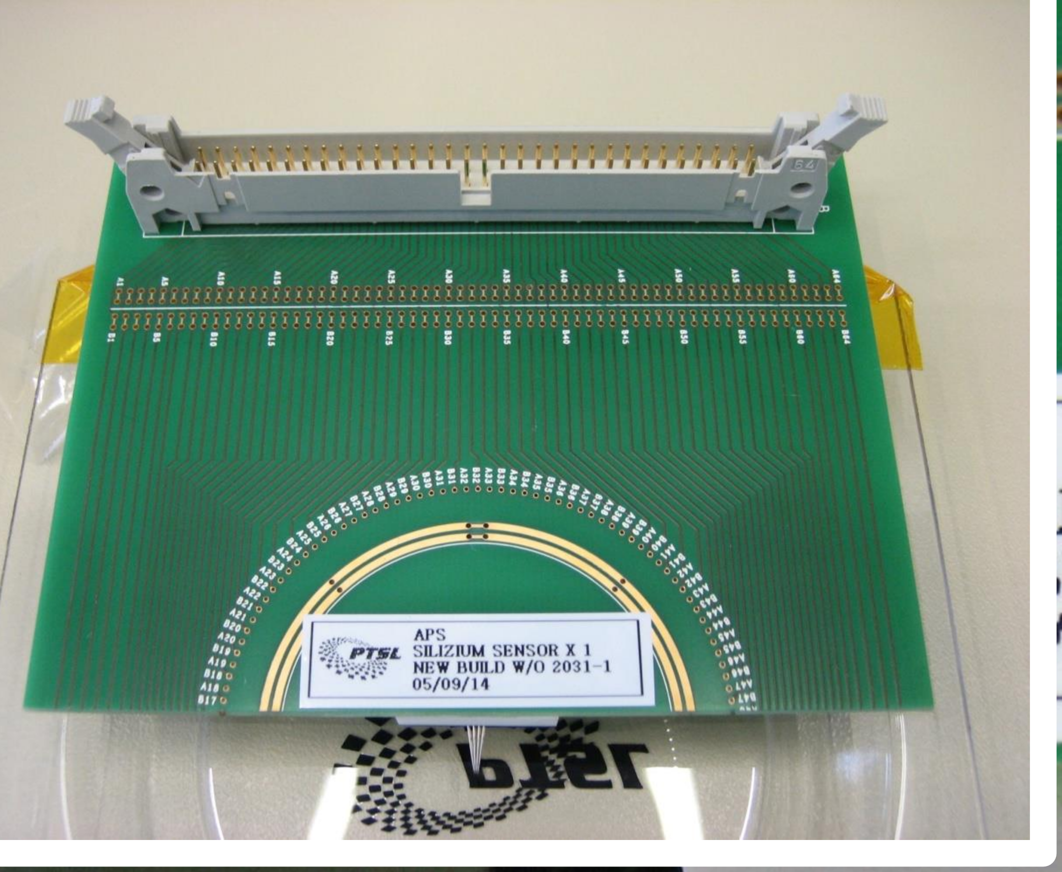


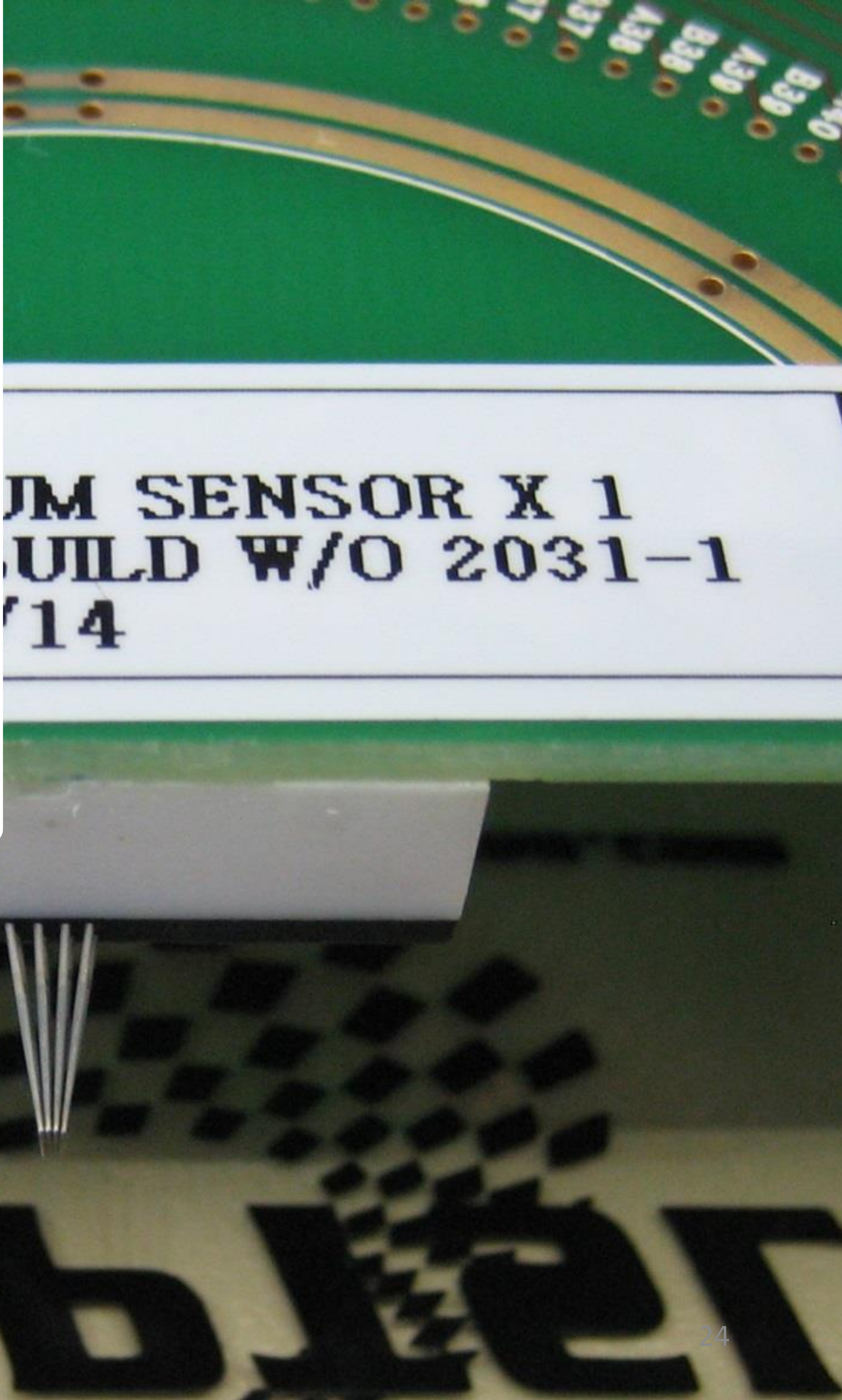
n side

fluence ($n_{eq}cm^{-2}$)	V_{fd} (V)	V_{bias} (V)	peak ADC p	±3	peak ADC n	eff. (%) p	±4	eff. (%) n
0	80±2	160±1	117		102	100		90
1×10^{13}	35±5	130±1	105		100	90		88
5×10^{13}	45±5	180±1	95		95	81		84
1×10^{14}	110±2	300±1	95		81	81		71

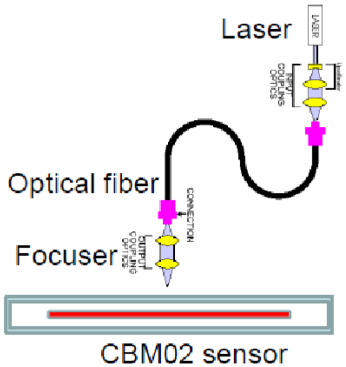
59.5 keV
117 ADC (p-side)
113 ADC (n-side)

S/N for MIP > 20

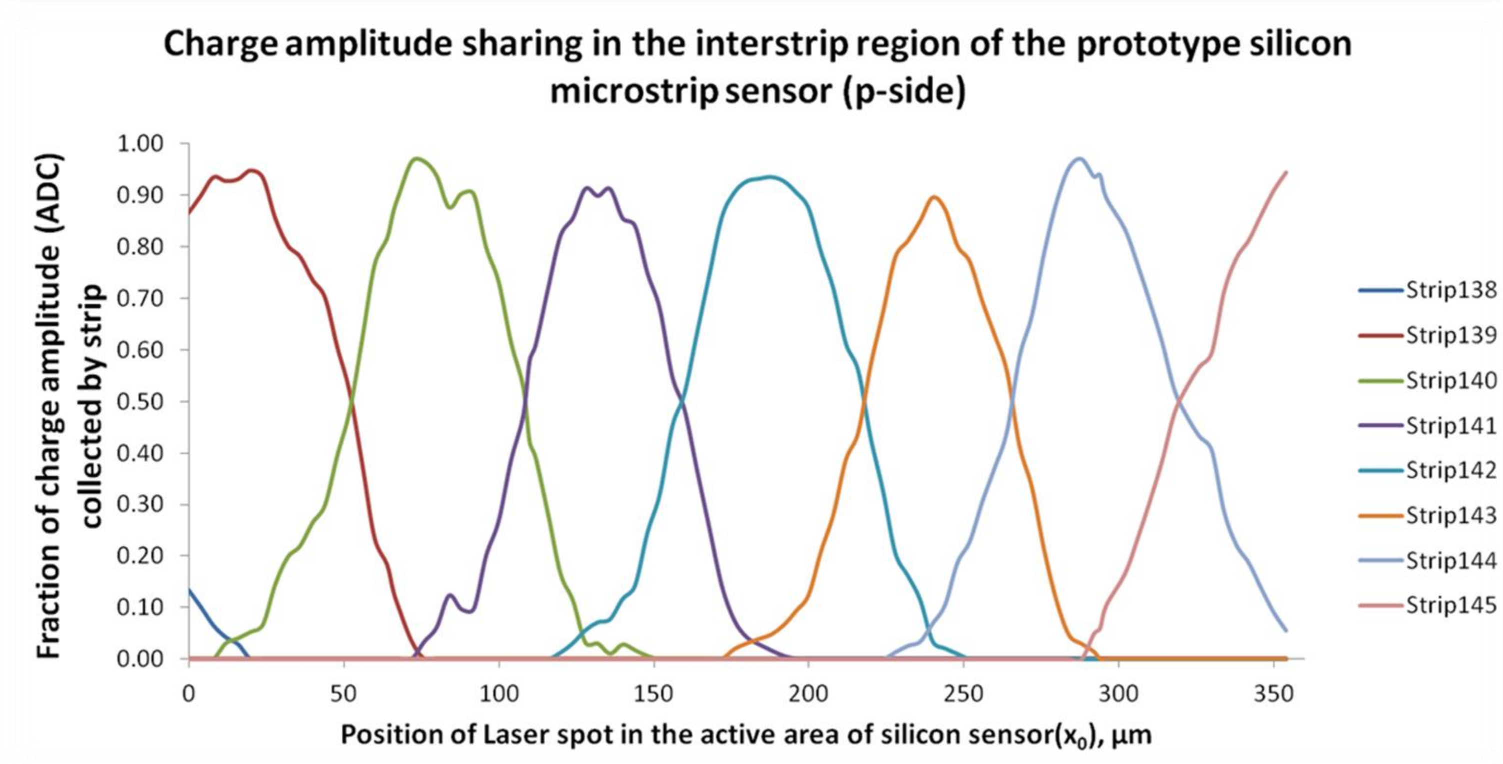

APS
SILIZIUM SENSOR X 1
NEW BUILD W/O 2031-1
05/09/14


UM SENSOR X 1
UILD W/O 2031-1
/14

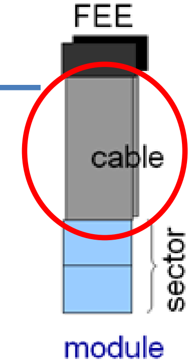
Laser tests – charge sharing



- dedicated laser test box with focused 1060 nm wavelength
- amount of charge as minimum ionizing particles

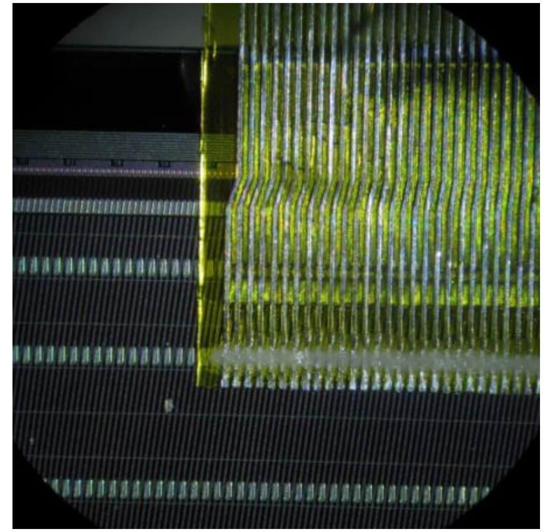


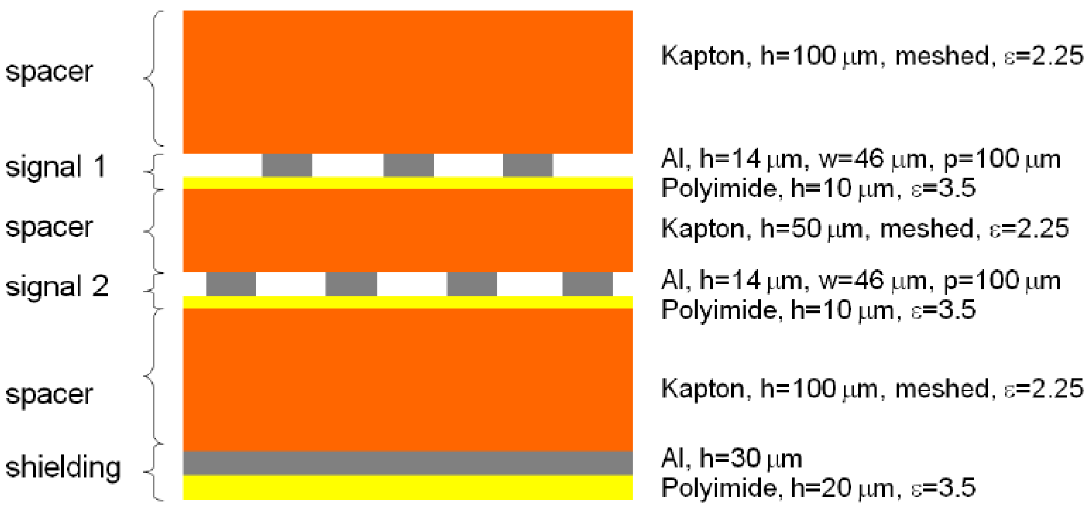
STS low-mass micro-cables

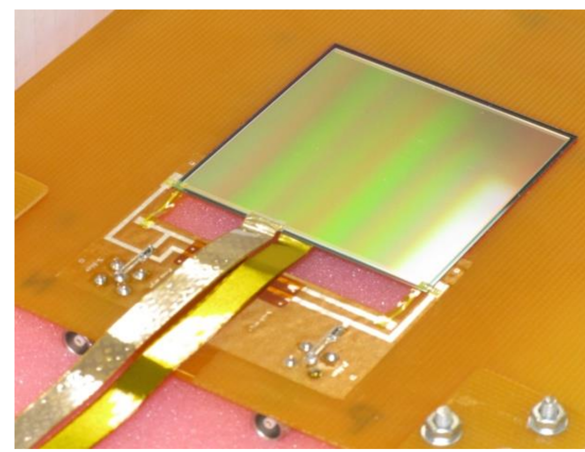


Cable

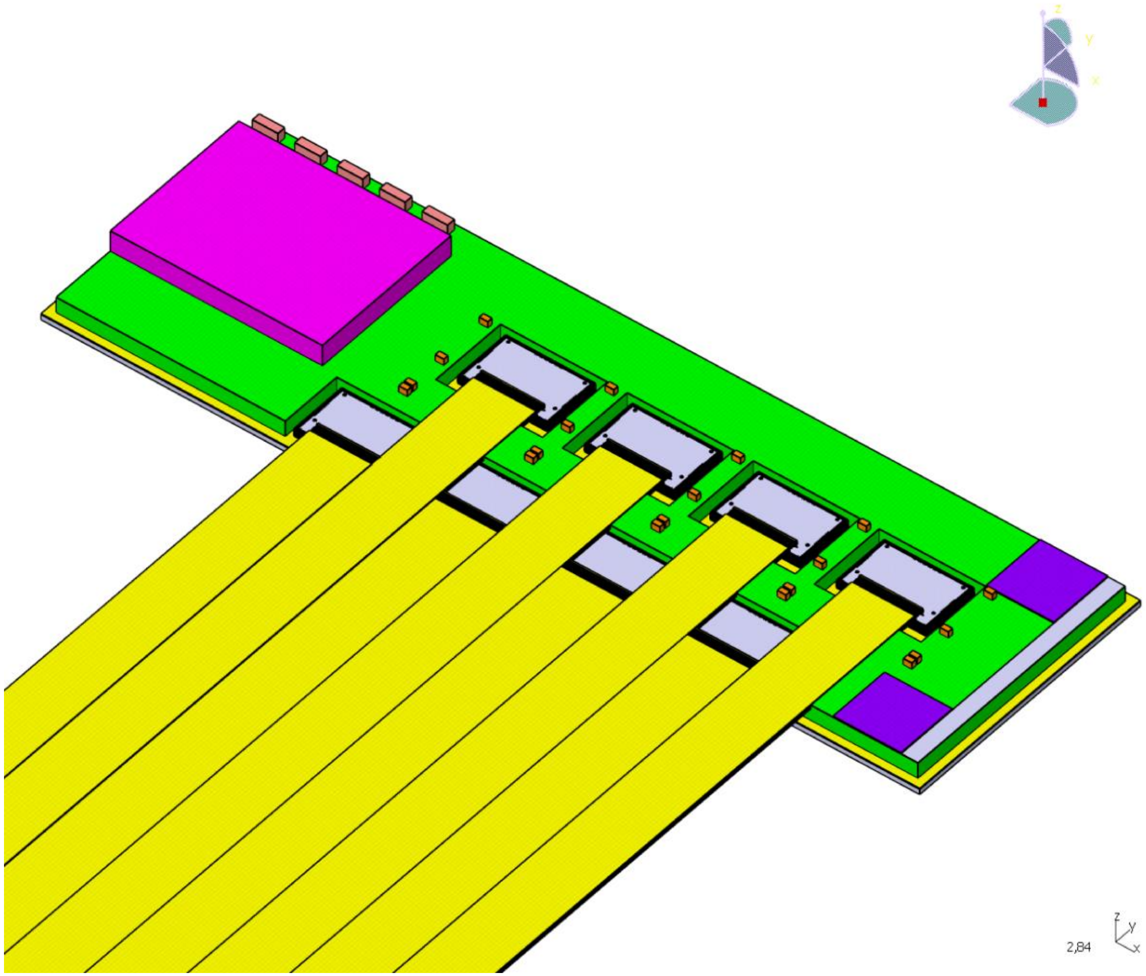
- radiation length: 0.1% X_0
- two signal layers
- strip pitch 116 µm, wire thickness 24 µm
- additional spacer to reduce the capacitance
- tap bonded to sensor
- 1024 channels to connect
- in prototypes 128 channels on each side are connected





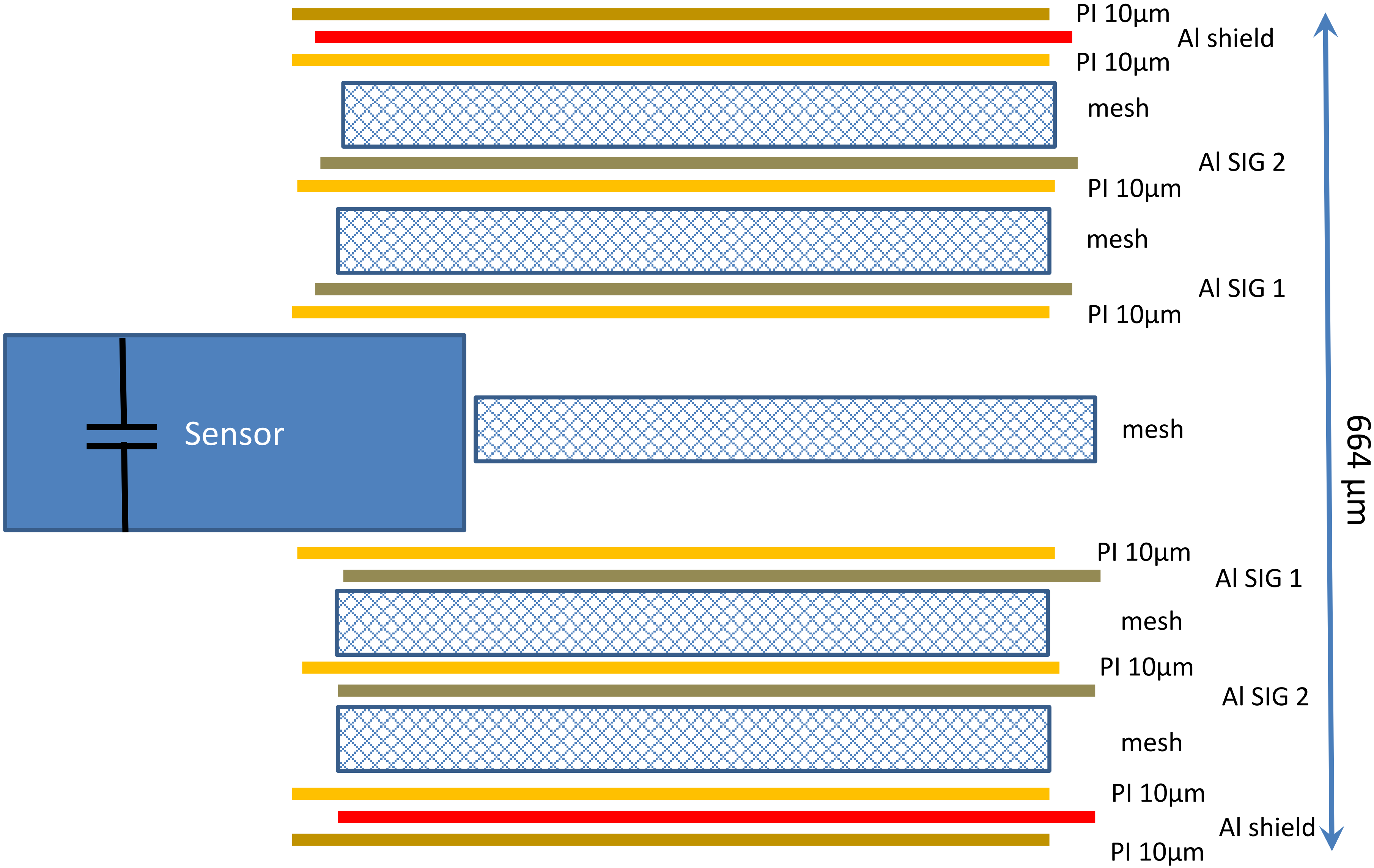


Connection of cables at FEB side



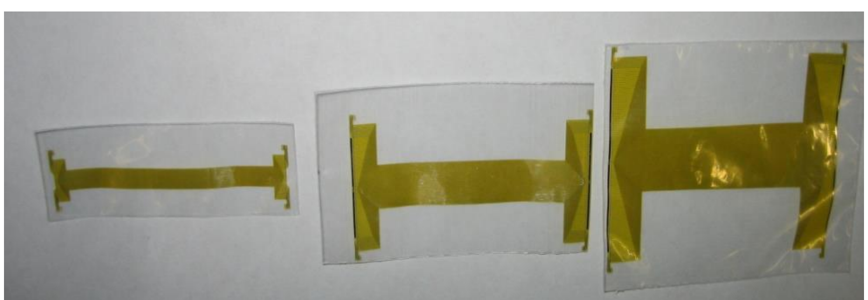
- On FEB side, chip arrangement suggests 64 lane cables
- Insertion into FEBs and wire bonding is last step

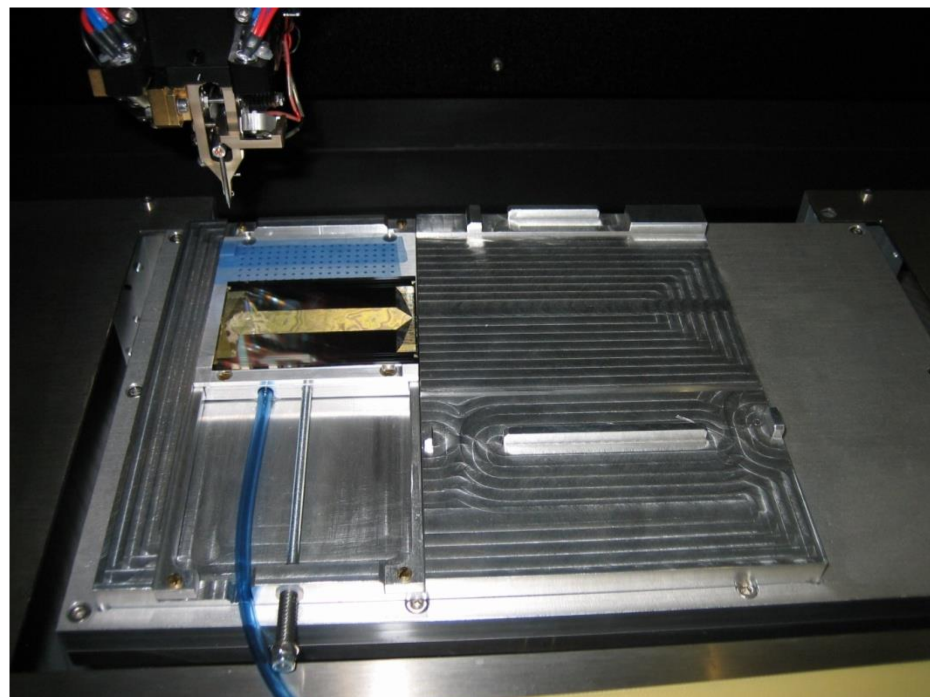
Module micro-cable stackup



Interstrip connection cables vs 2nd metal layer

- No risk of consecutive problems related to radiation damage ++
- Interstrip-Connection Cables rely upon same technology! ++
- In practice several problems appear: --
  - Interstrip Cables leave very little space for essential bond-support
  - Restricts order of assembly and adds complexity to manufacturing
  - Interstrip cables are much structured – to go around analogue cable attachment area.
  - Additional cable alignment tool needed
  - Interstrip cables never lie flat on sensor.
    → Alignment complicated





Connection cables for Daisy-chained sensors

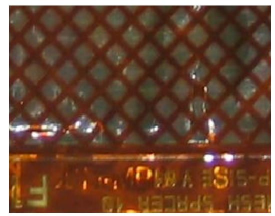
- 58µ line pitch
- Very narrow: 62mm x 5mm
- Alignment and bonding appears very challenging in serial production!

If daisy chaining can be avoided through 6 x 12 size sensors (pilot project at CIS), module assembly will result much easier!

Analogue Cable Spacer Material: Polypropylene ε_r=2.2

- need to add spacers between analogue cable layers to minimize stray capacitance → maximize S/N, minimize spacer thickness

- current concept: 100µm meshed Polyimide:
  ε_r effective =2.25



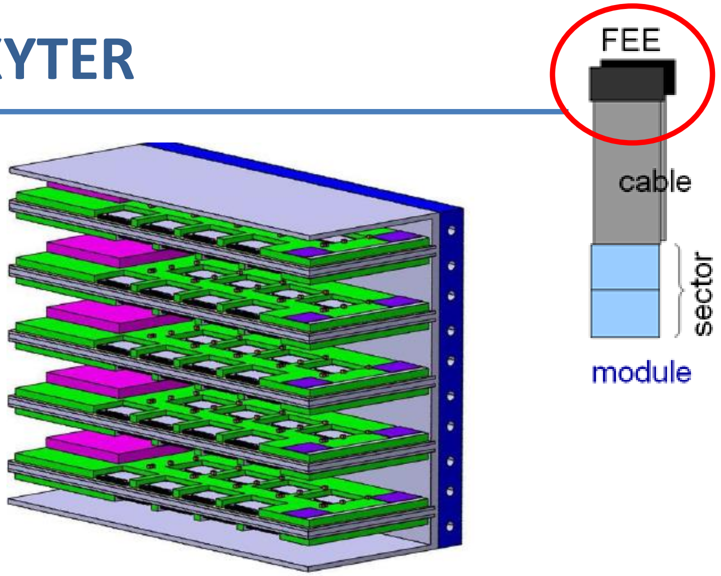
- alternative proposals:

- use cast polypropylene foil with ε_r=2.2
e.g. 50% meshed foil → **ε_r=1.6**

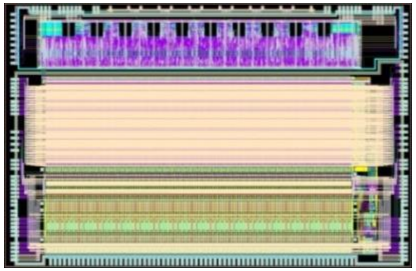
- use Teflon (ε_r=2.05) mesh → ε_r= 1.6 dep. on fillfactor
minimum thickness available 150µm

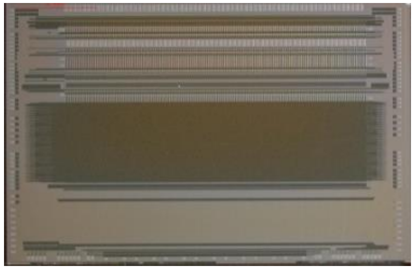
Could reduce C by 30% (S/N by 16%) or thickness of cable stack from 670 µm to 580 or 550 µm

Read-out chip STS-XYTER

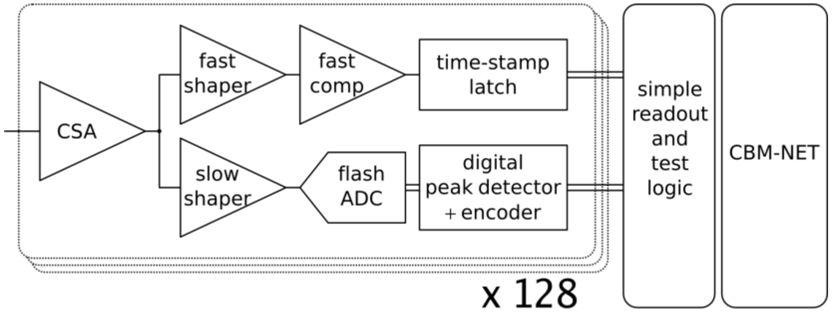


- full-size prototype dedicated to signal detection from the double-sided micro-strip sensors in the CBM environment
- fast ⇔ low noise ⇔ low power dissipation
- new w.r.t. n-XYTER architecture:
  - *effective two-level discriminator scheme*
- design V1.0 @ AGH Kraków
- *UMC 180 nm CMOS*

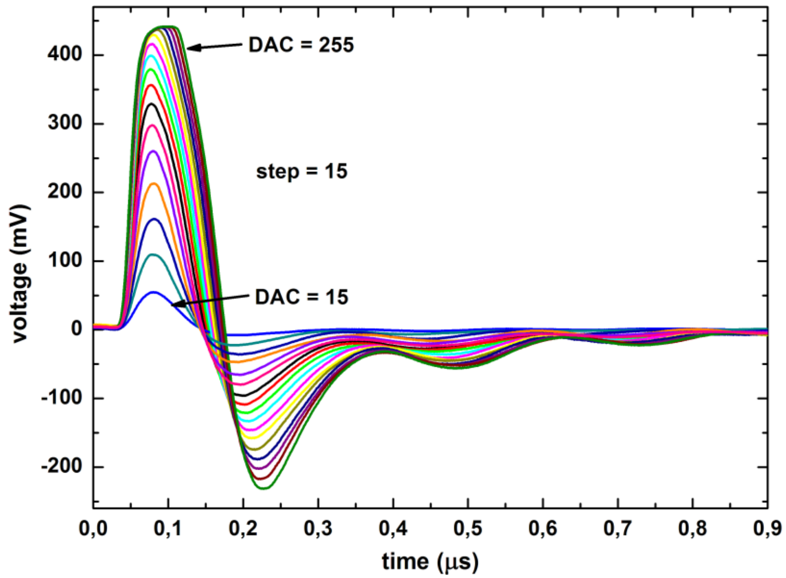




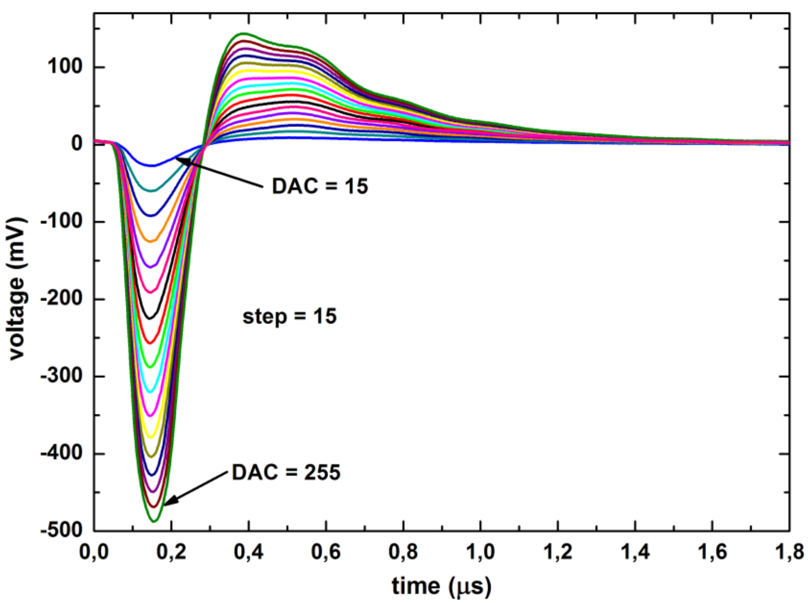
Channels, pitch	128 + 2 test
Channel pitch	58
Input signal polarity	+ and -
Input current	10 nA
Noise at 30 pF load	900 e^-
ADC range	16 fC, 5 bit
Clock	250 MHz
Power dissipation	4 mW/channel (analog)
Timestamp resolution	< 10 ns
output interface	4 × 500 Mbit/s LVDS



Read-out chip STS-XYTER

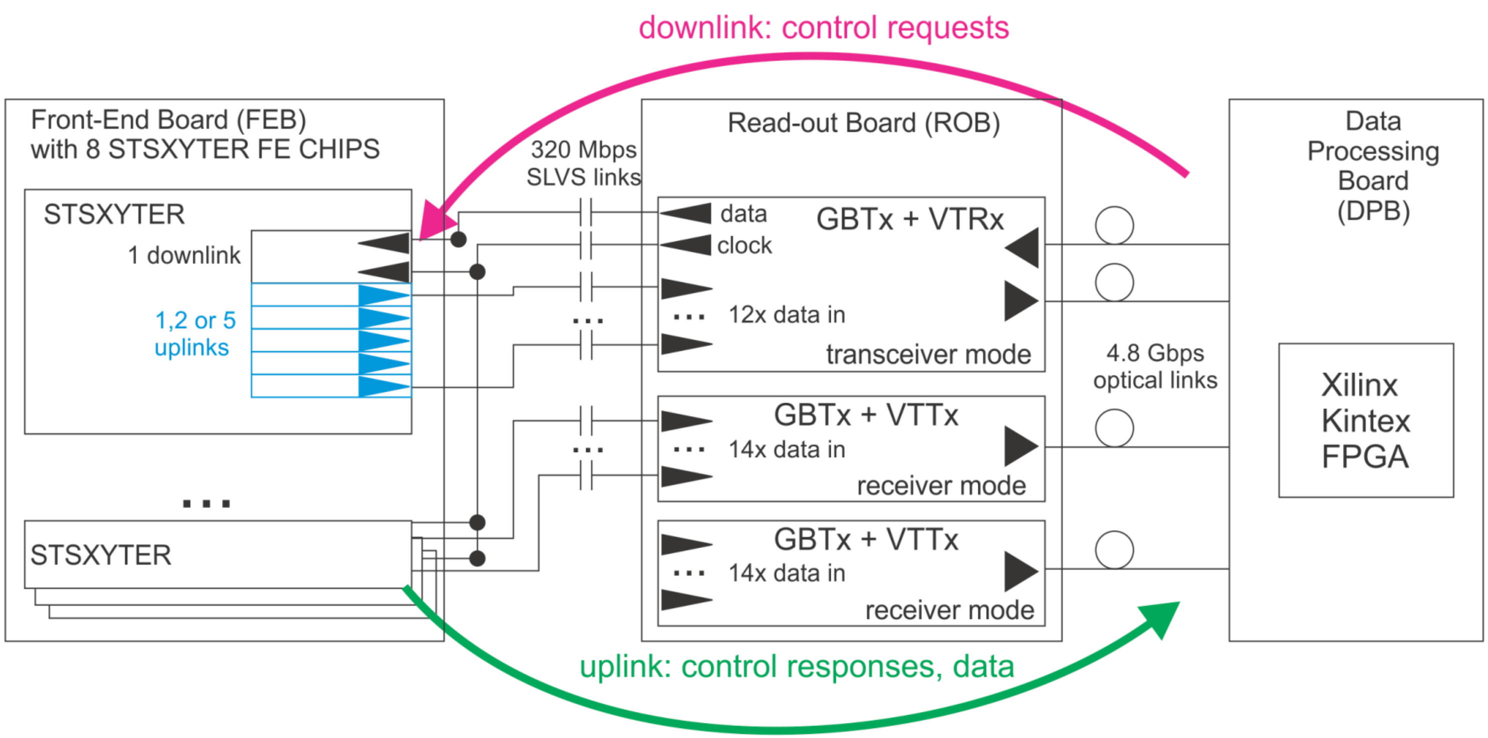


Fast shaper parameter	mean	std. dev.
gain [mV/fC]	71	0.94
t_P [ns]	30.5	0.1
t_W [ns]	108	-
ENC (CDET = 0)	315	0.66
ENC (CDET = 30 pF)	1037	2.1
v_{DC} [mV]	994	1.7

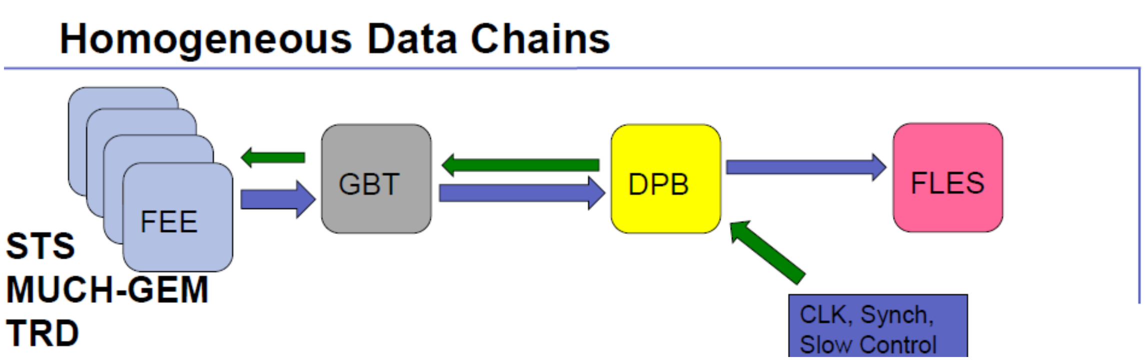


Slow shaper parameter	mean	std. dev.
gain [mV/fC]	34.9	0.47
t_P [ns]	79	0.14
t_W [ns]	343	-
ENC (CDET = 0)	197	0.6
ENC (CDET = 30 pF)	600	1
v_{DC} [mV]	994	4

GBTx based interface

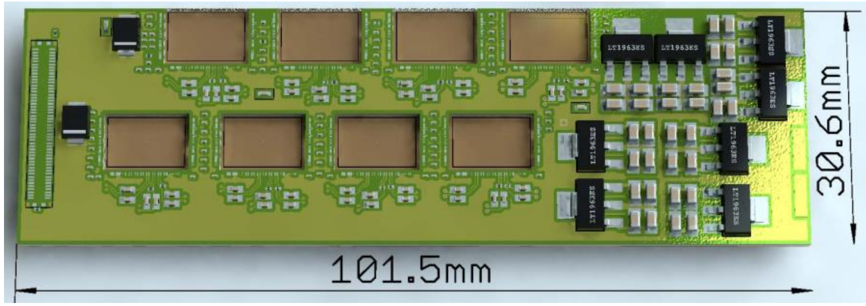


Protocol is developed in cooperation of AGH with Warsaw University of Technology



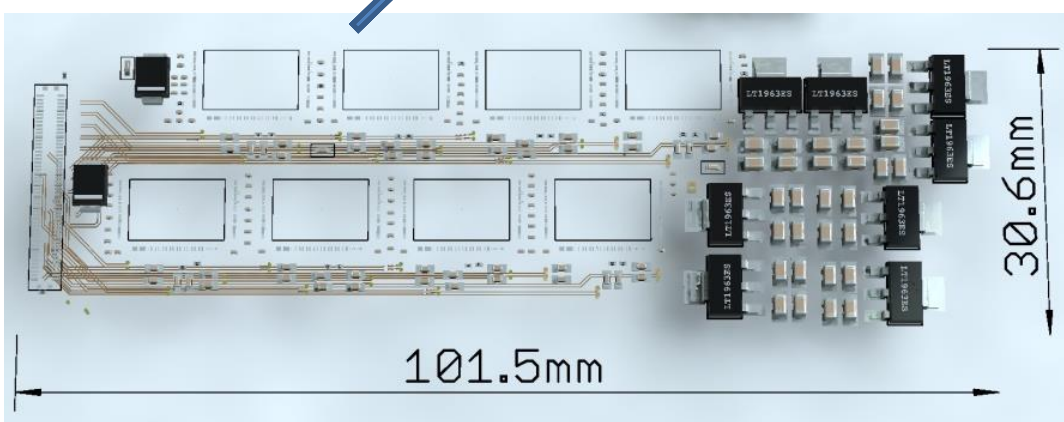
STS-XYTER – DPB talk via E-link @320MHz (1,2 or 5 per ASIC)
The presence of GBTx ASIC is transparent from data point of view.

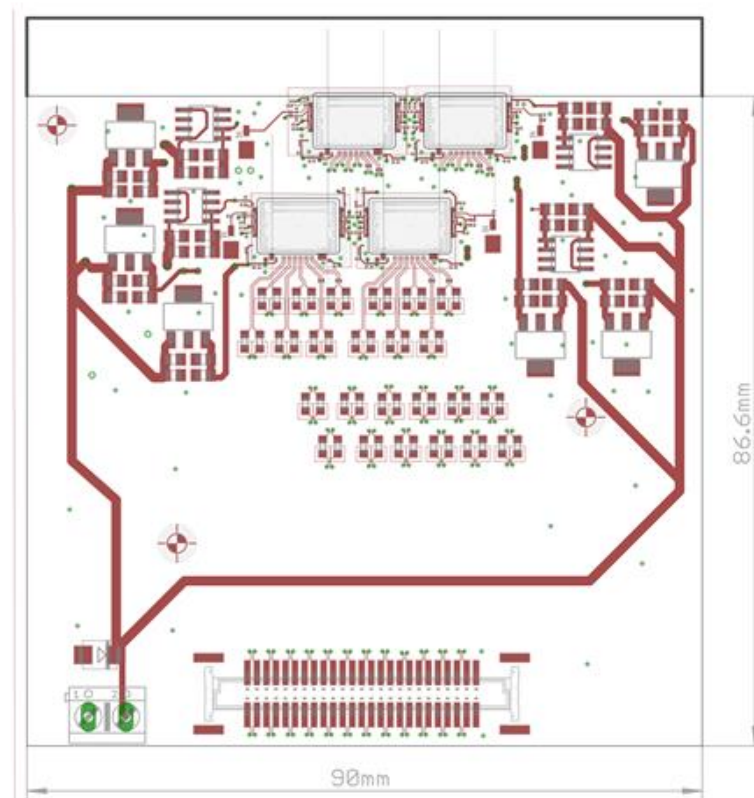
GBTx based interface



- "FEB-5" is an enormous routing challenge with 8 ASICs
- 4-STS-XYTER prototyping FEB to evaluate sensor readout (full chip readout)
- Where to allocate all the coupling Caps (300V caps are big)

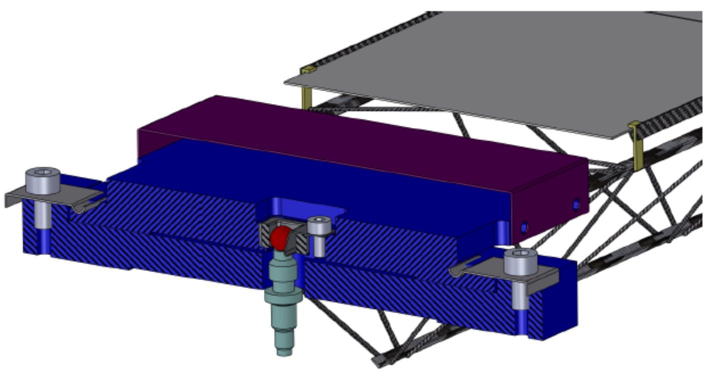
5 LVDS output lines per ASIC

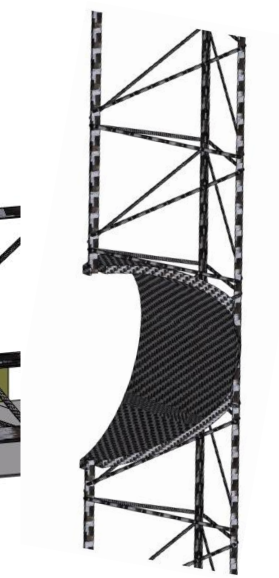




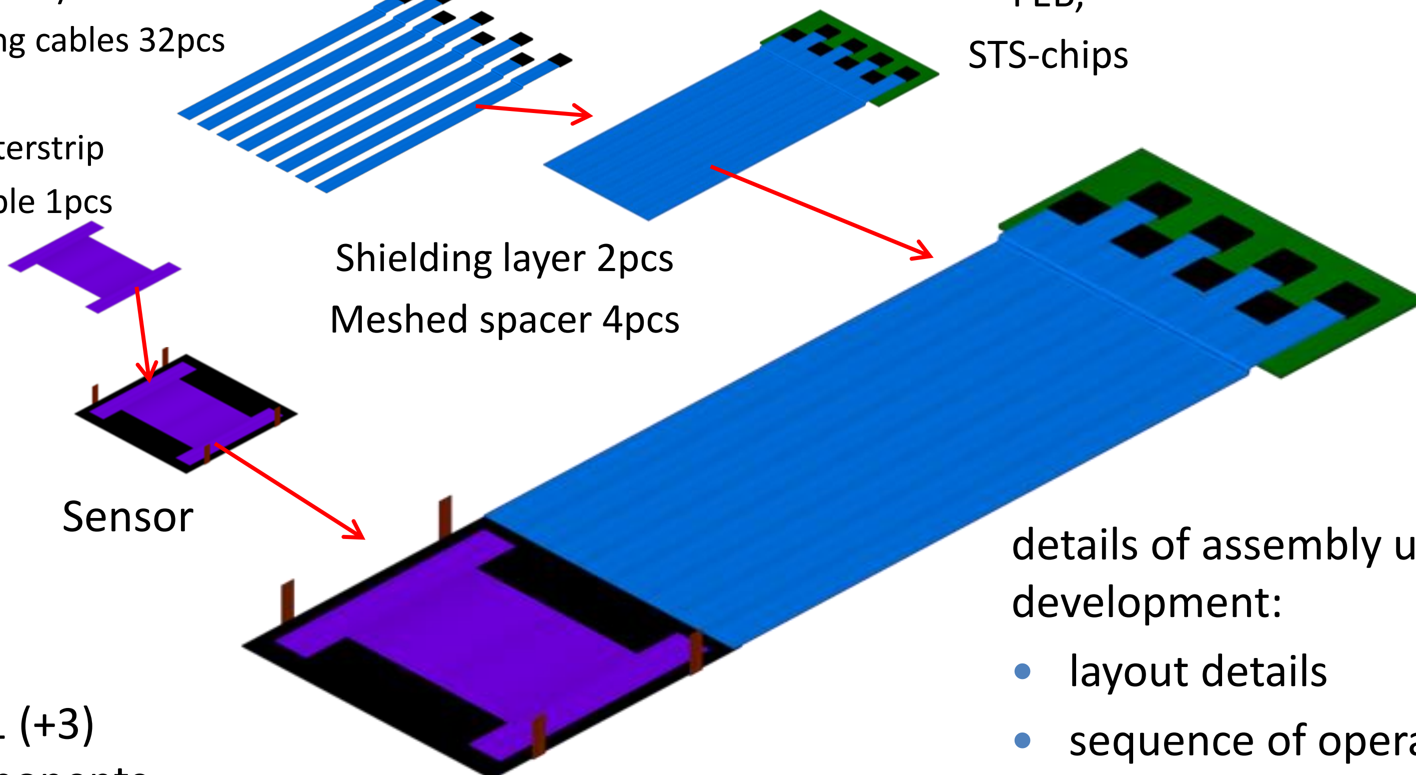
Ladders

- lightweight carbon-fiber space frames with end supports
- ladder comprises two times five modules
- one-cycle polymerization at 125 °C in a metallic mold
- modules are attached using L-legs





Module assembly process



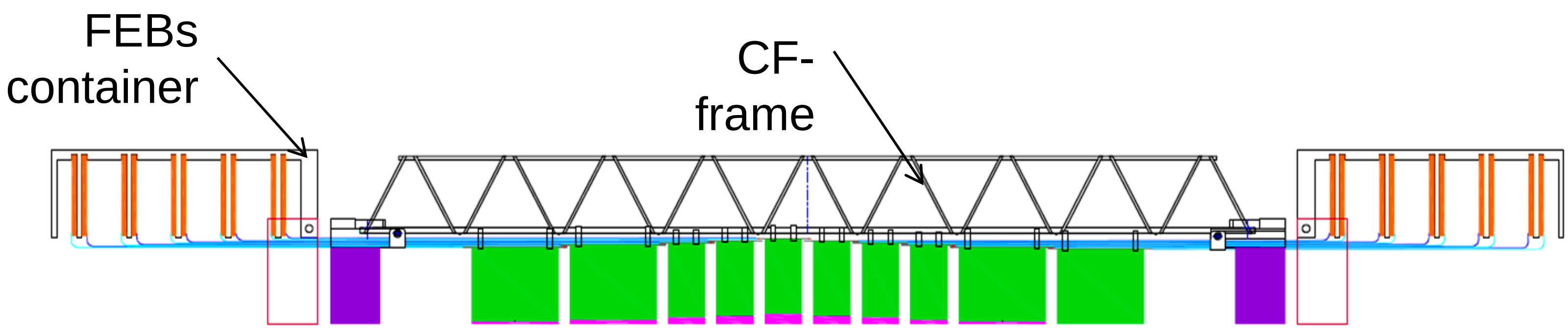
71 (+3)
components
per module

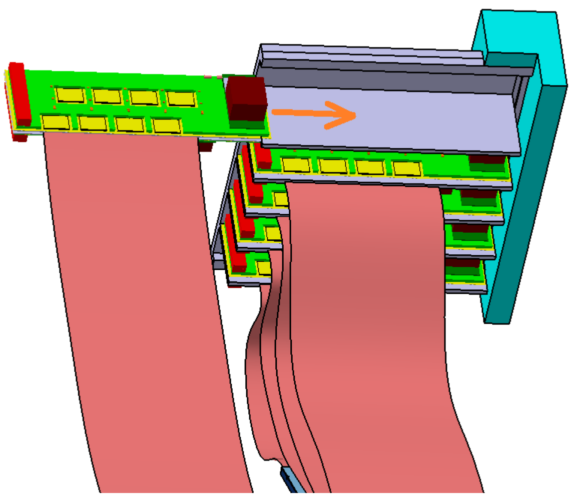
details of assembly under development:

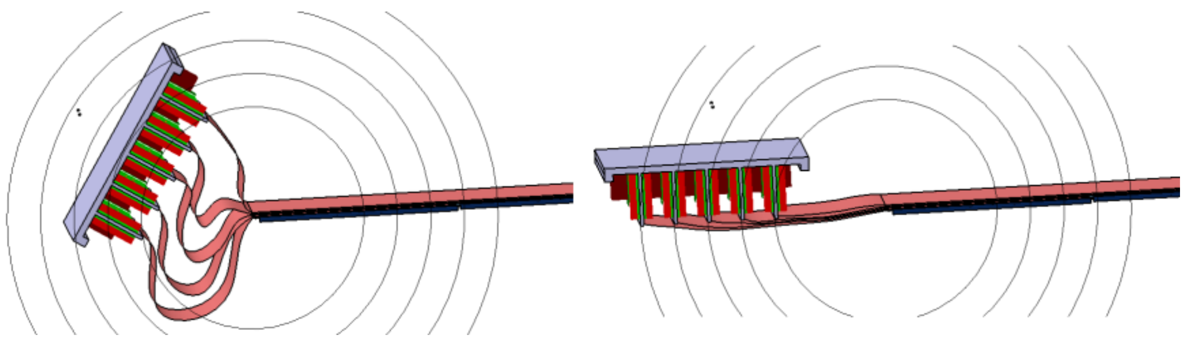
- layout details
- sequence of operations?
- materials, tooling
- **yields**
- monitoring of accuracy
- practical experience required

Ladder assembly process

- mounting of modules onto carbon fiber support ladders



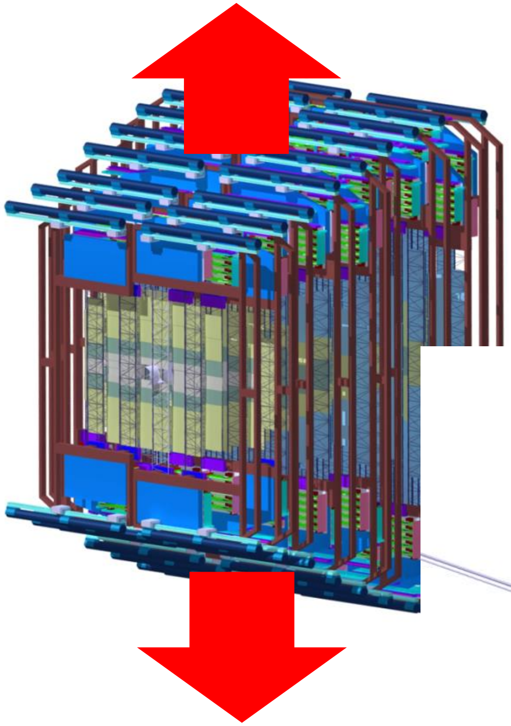




- assembly procedure under study (JINR): fixture to hold electronics while attaching modules to CF frame
- assembly tools, preparation of technical tasks for PLANAR, Minsk

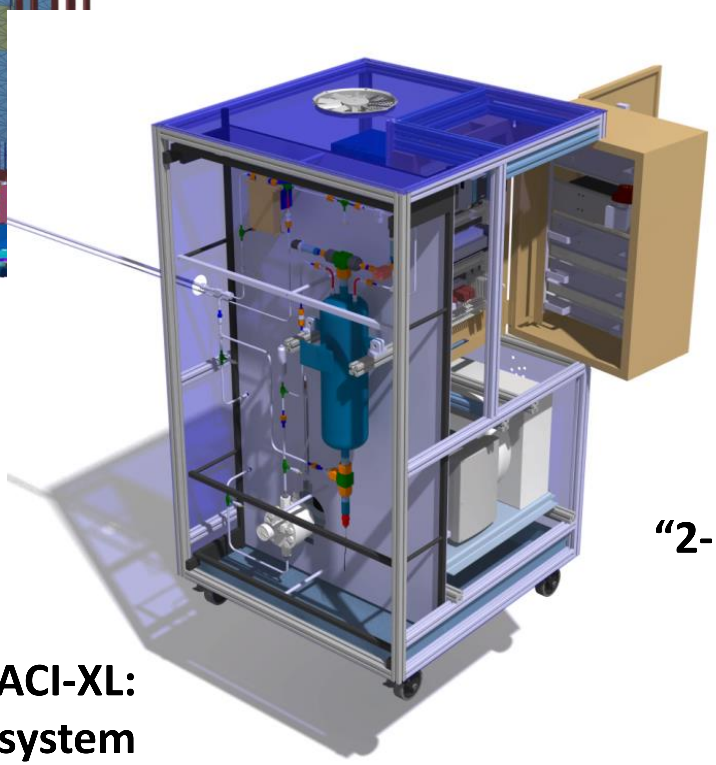
Cooling

20 kW

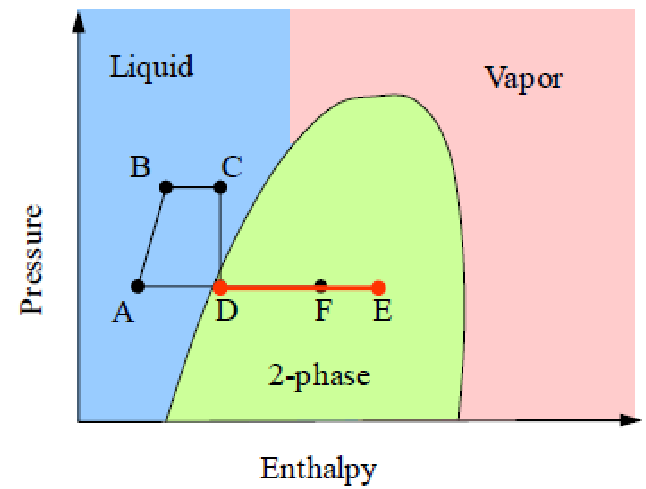


20 kW

- STS read-out electronics dissipates ca. 40 kW
- cooling with bi-phase CO2:
  - high efficiency at small spatial requirement
- standard for tracker upgrades at LHC
- cooperation of GSI with CERN: TRACI-XL



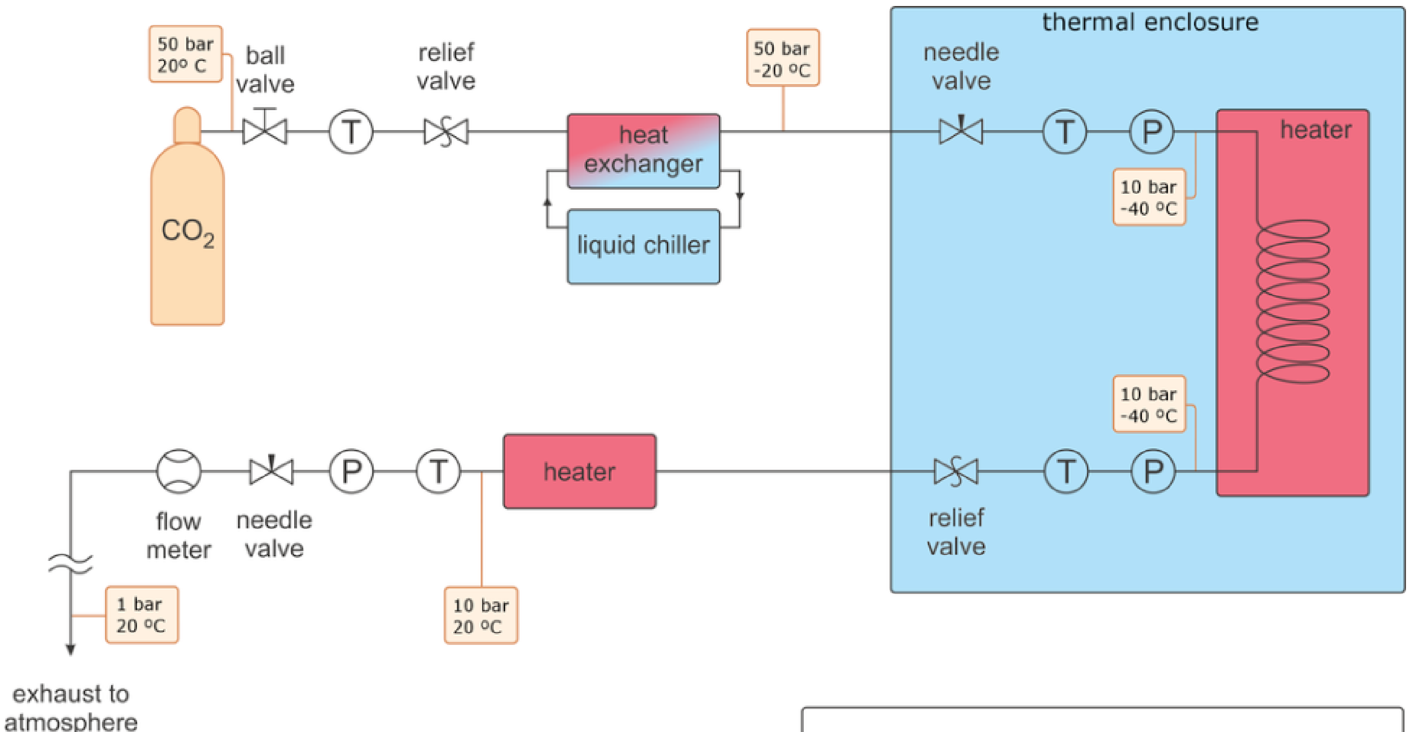
TRACI-XL:
1 kW test cooling system

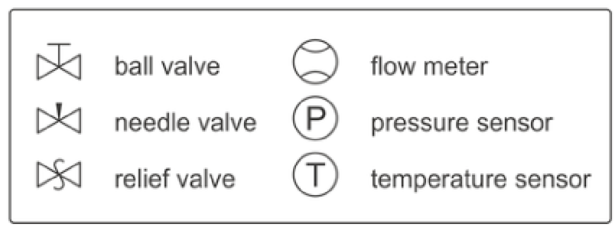


"2-phase accumulator controlled loop"

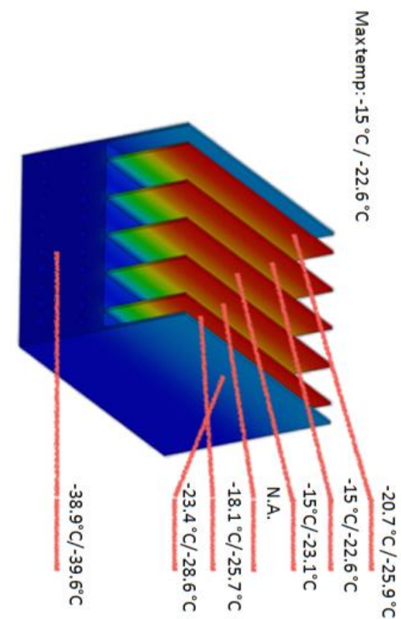
EU-FP7 CRISP
Work Package CO_2 cooling
http://www.crisp-fp7.eu/

FEB box cooling demonstrator





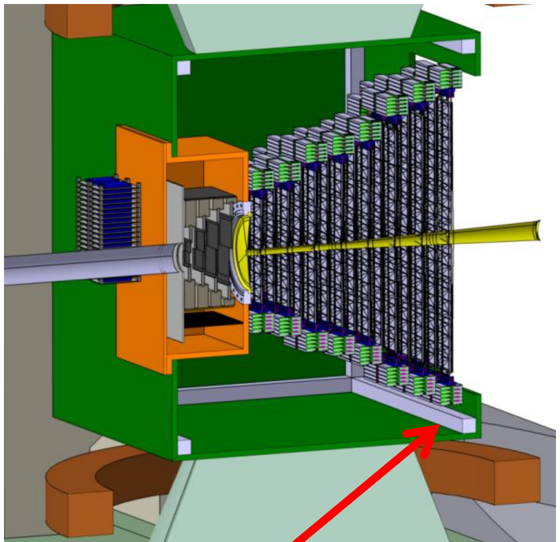
at Univ. Tübingen:
open blown CO_2
cooling system



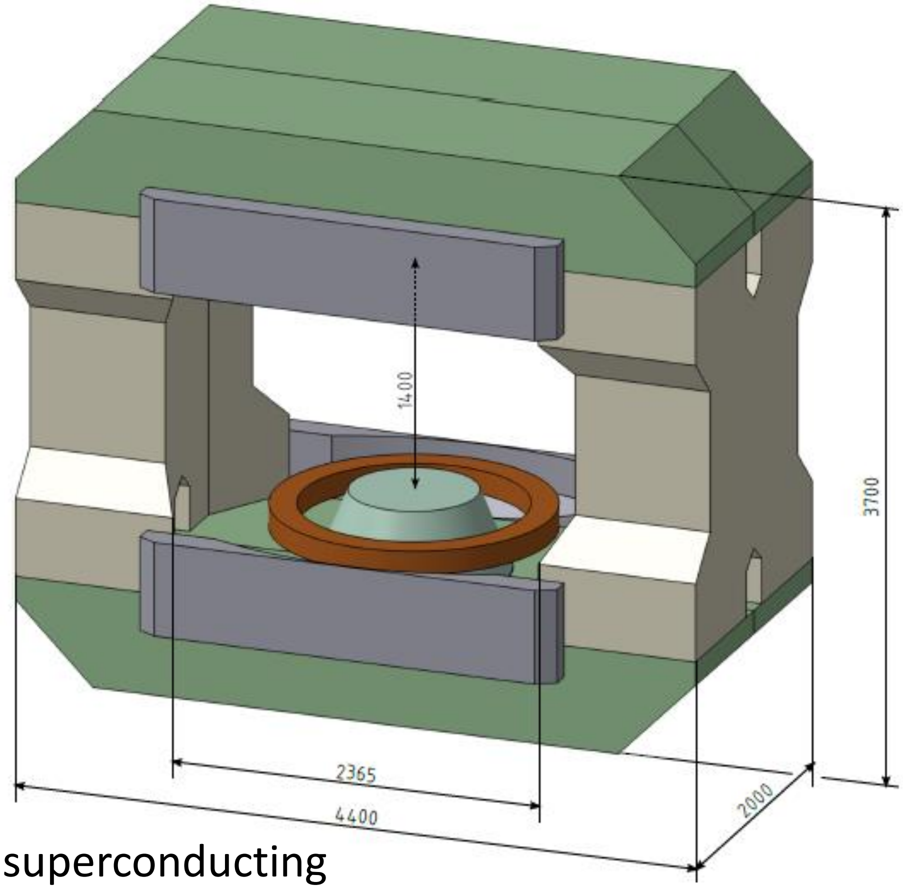
FEB box simulator, 200 W

A lot of different designs simulated
Tests with so far 4 different FEB-box design
Very good results for 3mm design
Proposed to use in production.

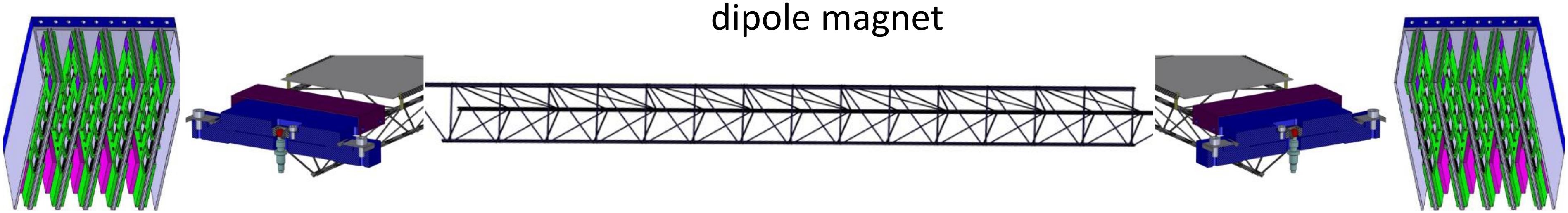
Vertical space restrictions



Last station duplet (7 & 8)
has height of ladders up to 95cm

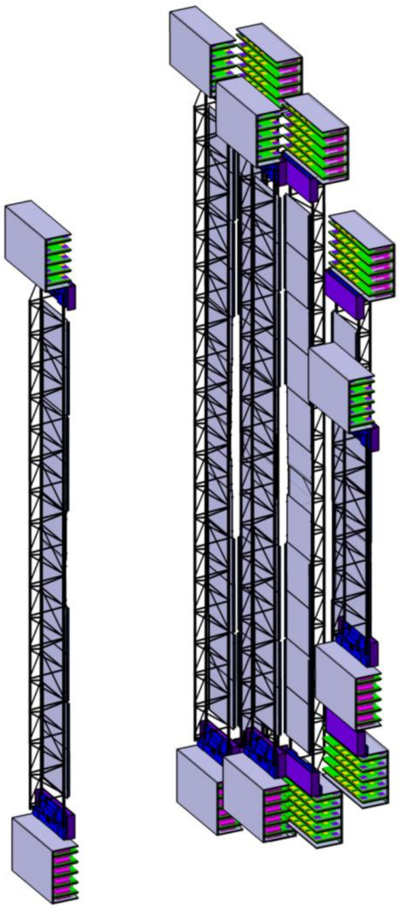


H-type superconducting
dipole magnet

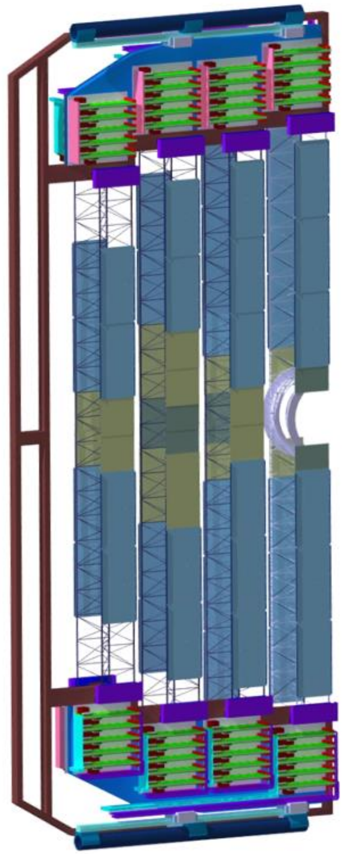


Approx 120 cm (without cables, thermal insulation, rails, walls of STS box)

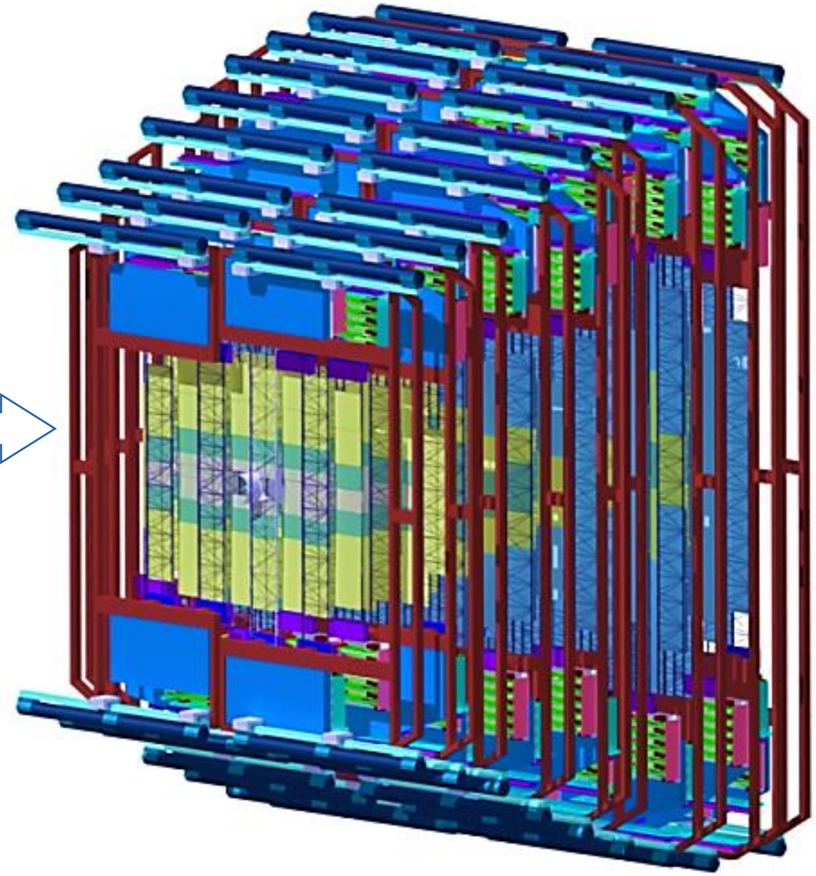
Station assembly process



Ladders



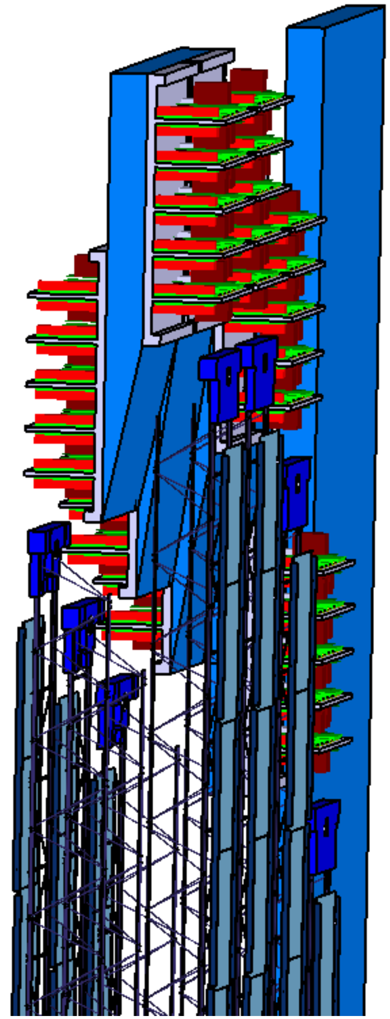
Unit

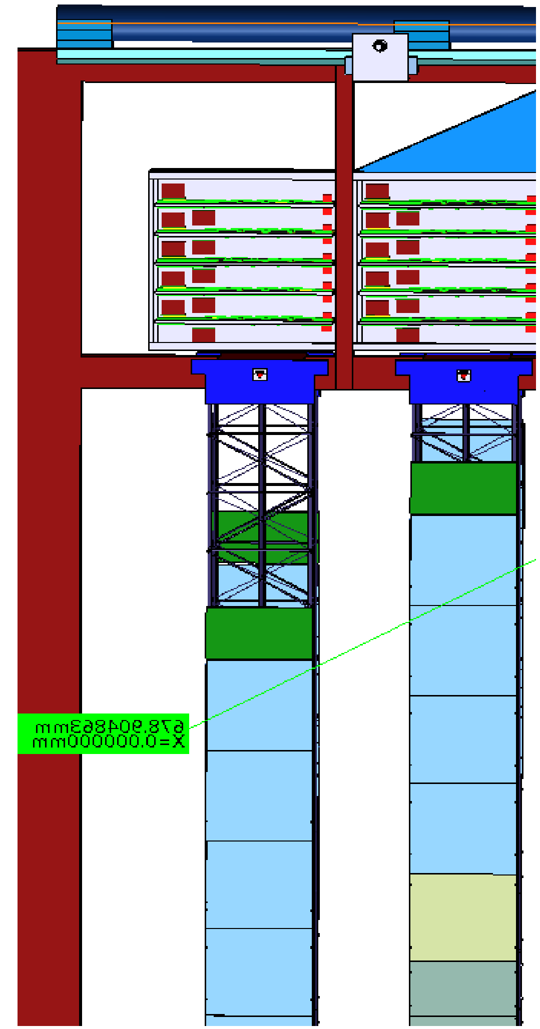


System with 8 stations

Routing

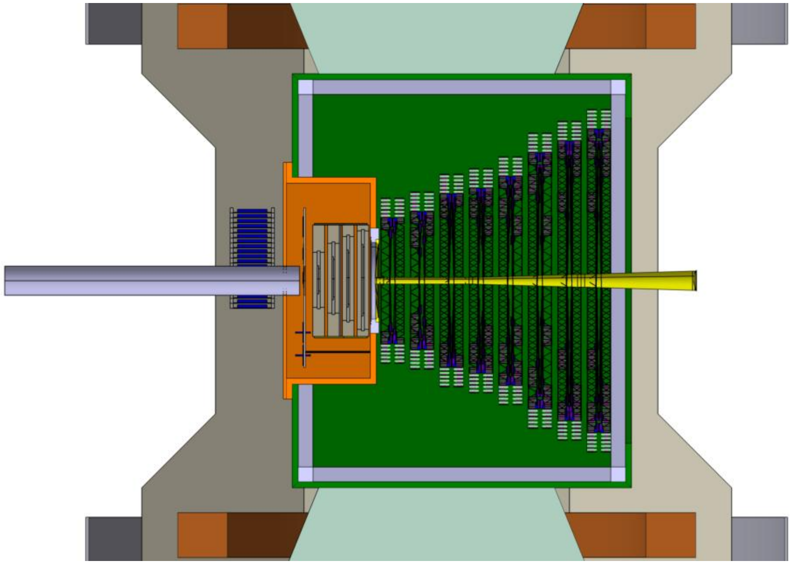
Mockup

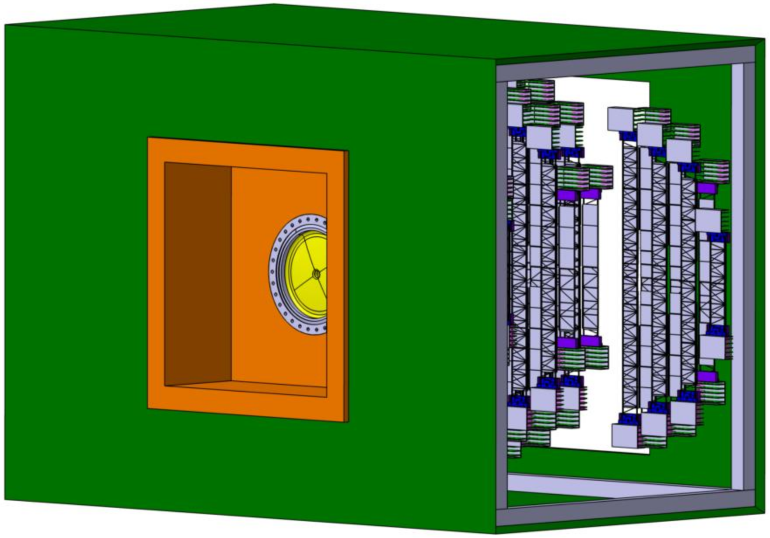




System Integration

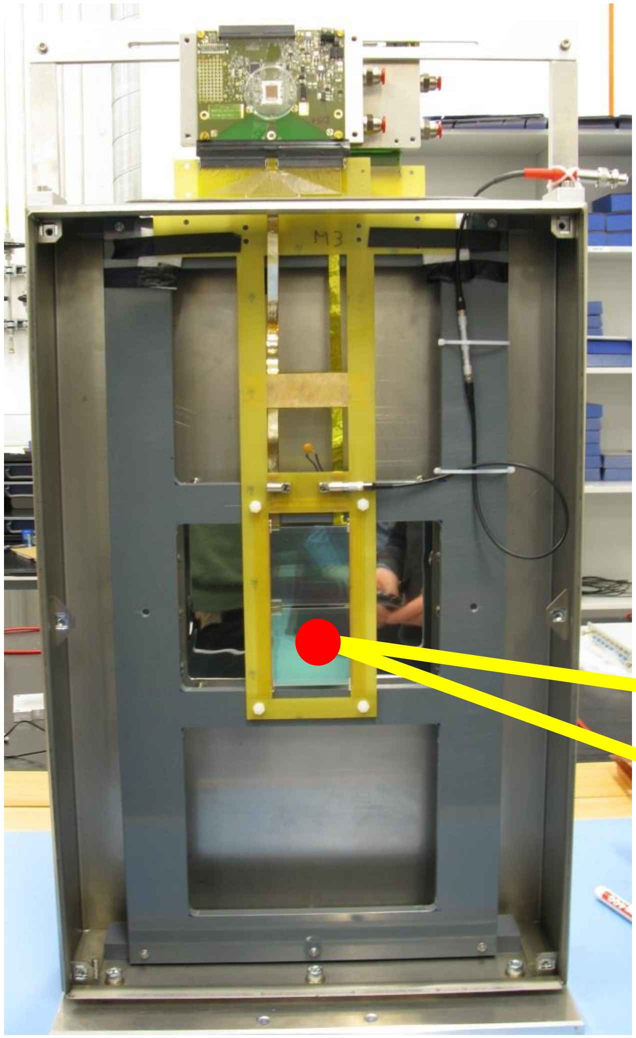
- very active work-team
- many tasks:
- overall system concept:
  - STS stations/units
  - space frame, thermal enclosure
  - connectivity, routing of services
  - cooling of electronics and sensors
- tasks:
  - elaboration and freezing of concepts and dimensions
  - construction of demonstrators/mock-ups
  - feedback simulations (coverage, stability, alignment) to engineering

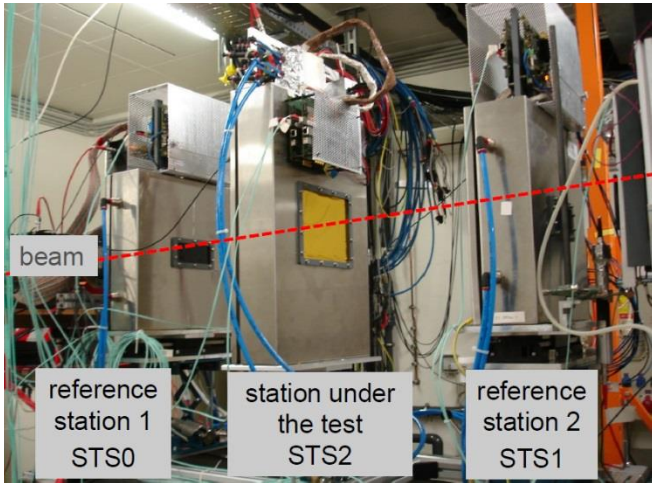




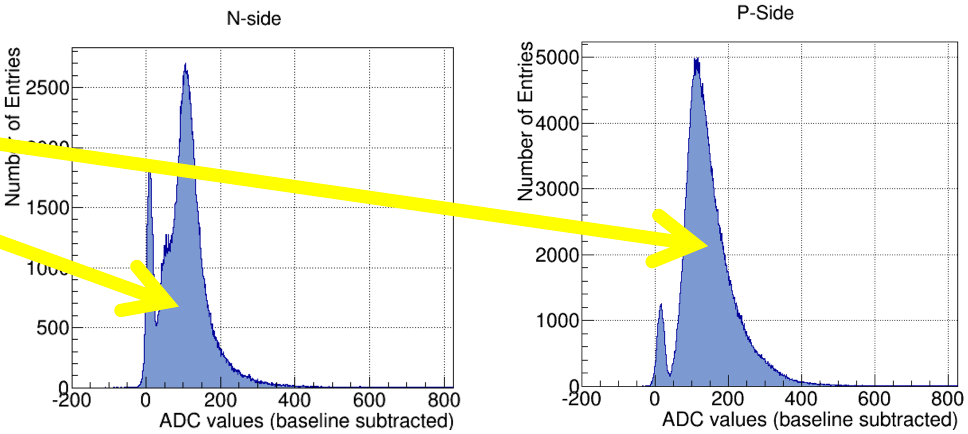
Module prototype tests

- Module prototype with CBM05 sensor and second batch of the low-mass micro-cables and n-XYTER FEB



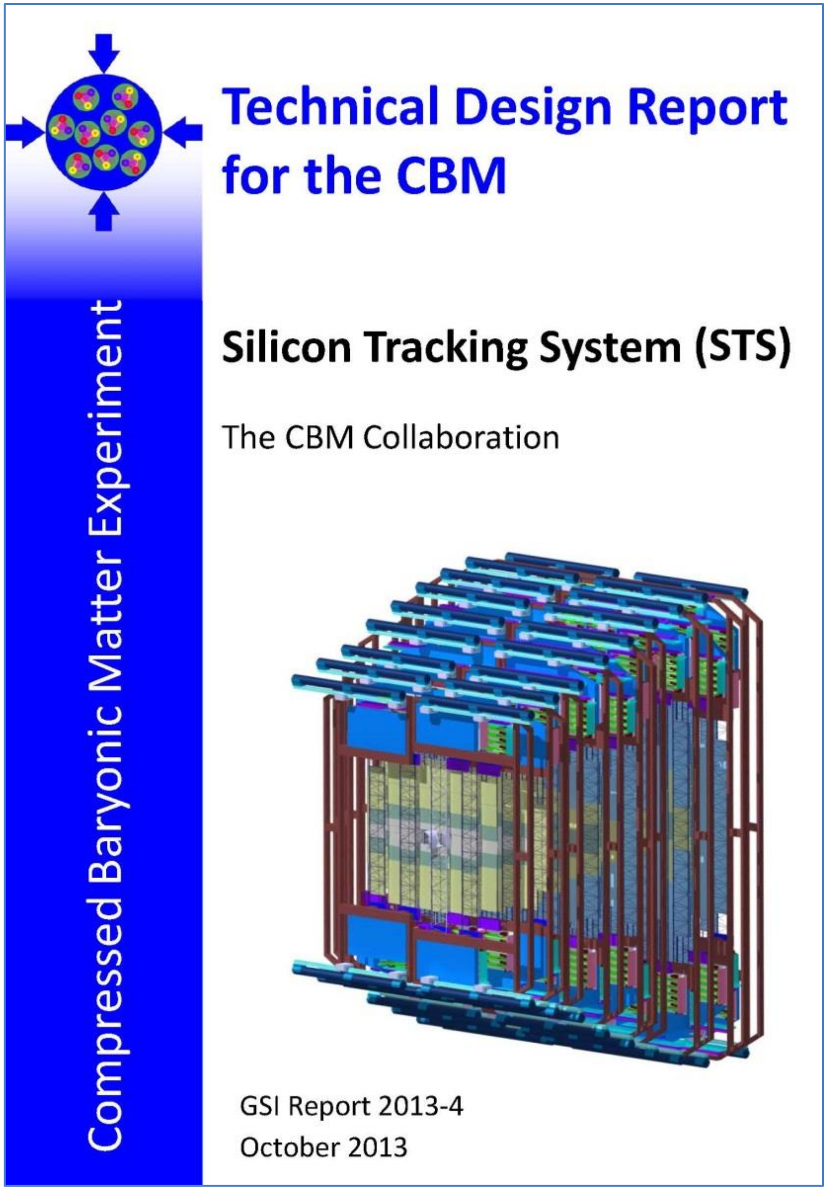


COSY @ Jülich



STS Technical Design Report

Approved by FAIR



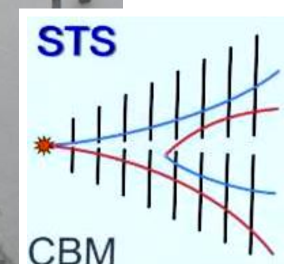
TDR signed by

- *77 authors*
- *from 15 institutes in Germany, Poland, Russia, Ukraine*

new participants since then:

- *new group members*
- *KIT as new institute*

Compressed Baryonic Matter Experiment



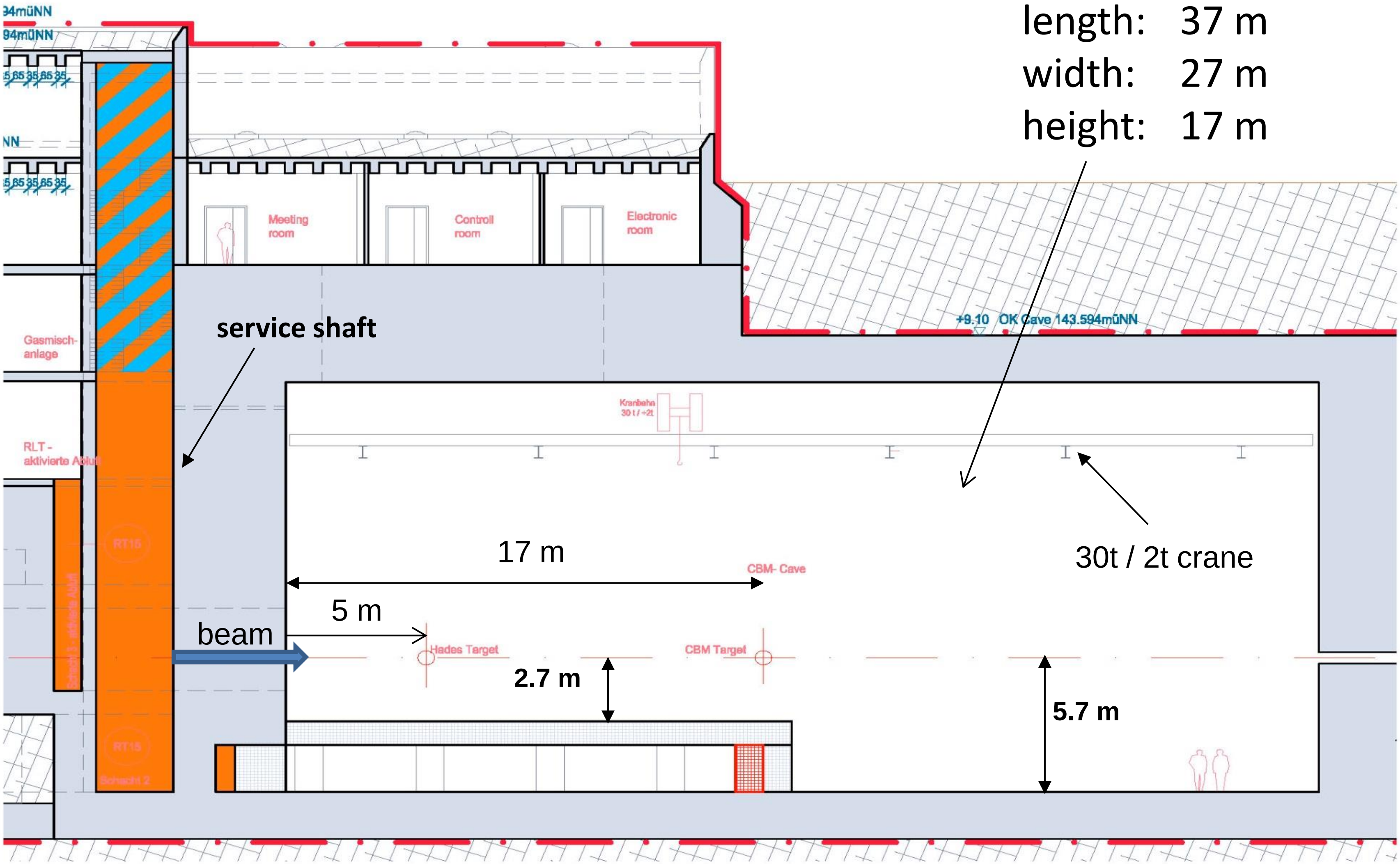
Institutes participating in the CBM-STS project

From Germany, Poland, Russia, Ukraine:

- *Darmstadt, Germany, GSI Helmholtz Center for Heavy Ion Research GmbH*
- *Dubna, Russia, Joint Institute for Nuclear Research (JINR)*
- *Katowice, Poland, University of Silesia*
- *Kharkov, Ukraine, LTU Ltd* * *Partner Institut*
- *Kiev, Ukraine, Kiev Institute for Nuclear Research (KINR)*
- *Krakow, Poland, AGH University of Science and Technology*
- *Krakow, Poland, Jagiellonian University*
- *Moscow, Russia, Institute for Theoretical and Experimental Physics (ITEP)*
- *Moscow, Russia, Moscow State University*
- *Protvino, Russia, Institute for High Energy Physics (IHEP)*
- *St. Petersburg, Russia, Ioffe Physical-Technical Institute*
- *St. Petersburg, Russia, Khlopin Radium Institute (KRI)*
- *St. Petersburg, Russia, St. Petersburg State University*
- *Tübingen, Germany, Eberhard Karls University*

Backup

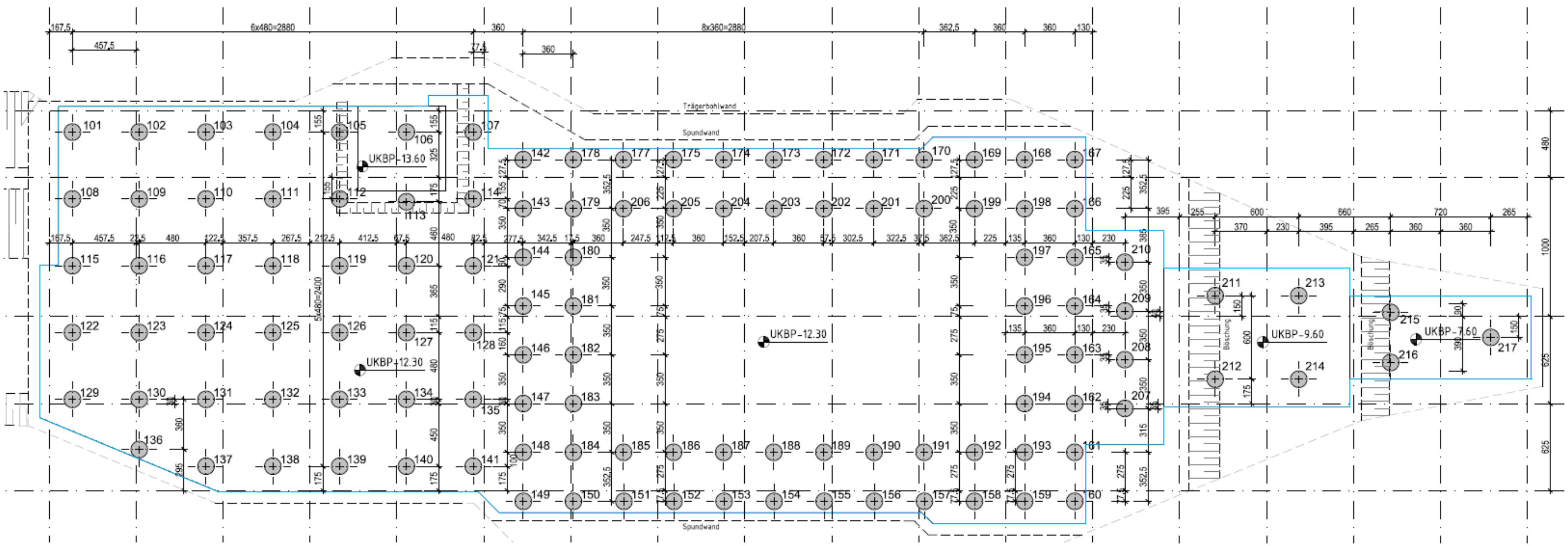
CBM Cave, side view



Piles diagram

finished drilling 1350 piles for FAIR and 115 piles for CBM

Pfahlübersicht



Piles

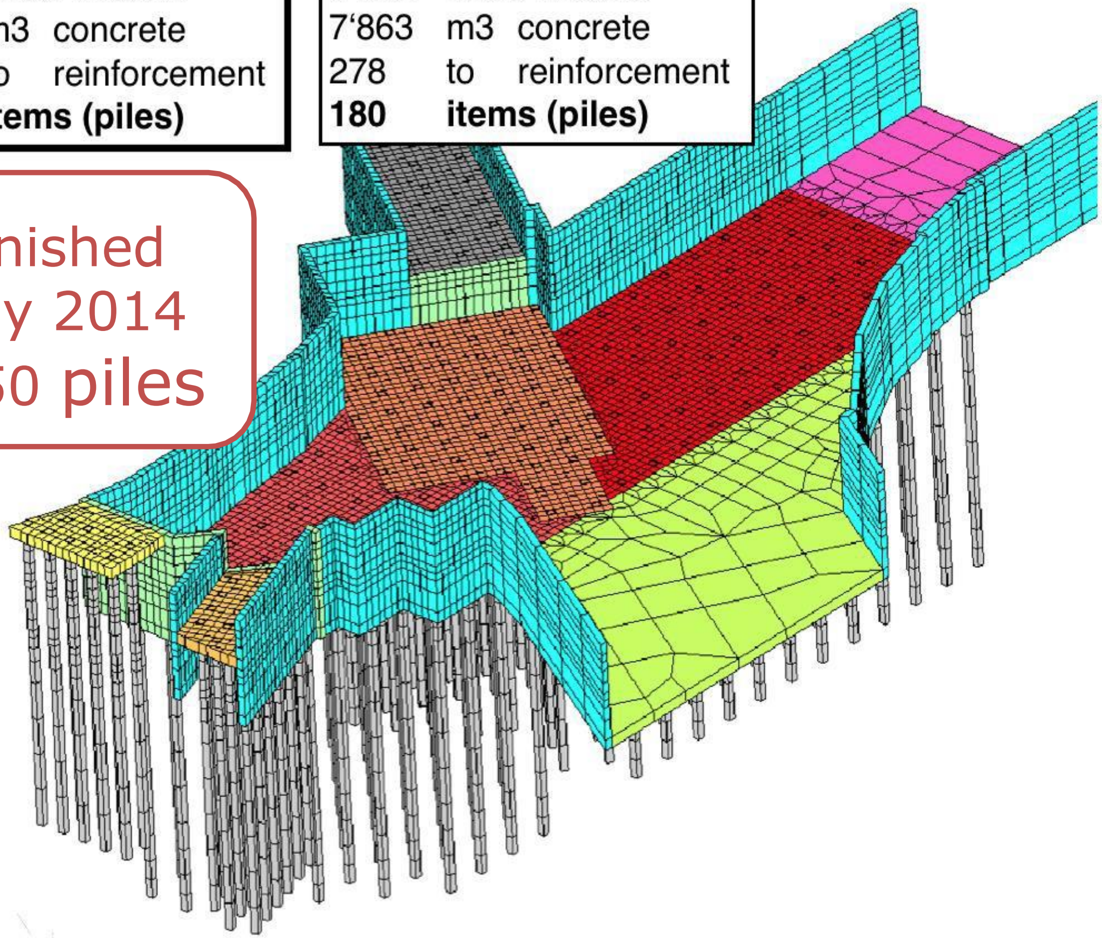
Status 28.11.2013:

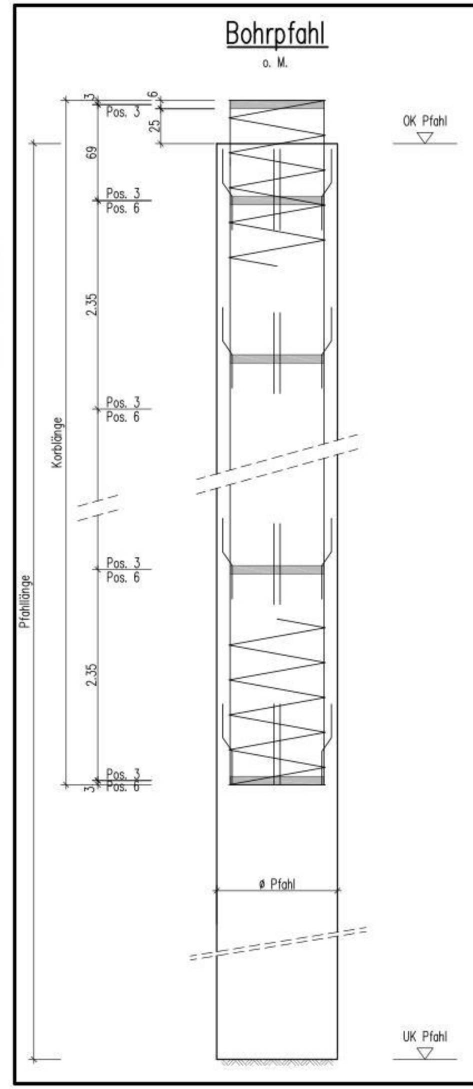
26‘620 linear meters
30‘100 m3 concrete
740 to reinforcement
692 items (piles)

Status 28.6.2013:

6‘953 linear meters
7‘863 m3 concrete
278 to reinforcement
180 items (piles)

Finished
May 2014
1350 piles

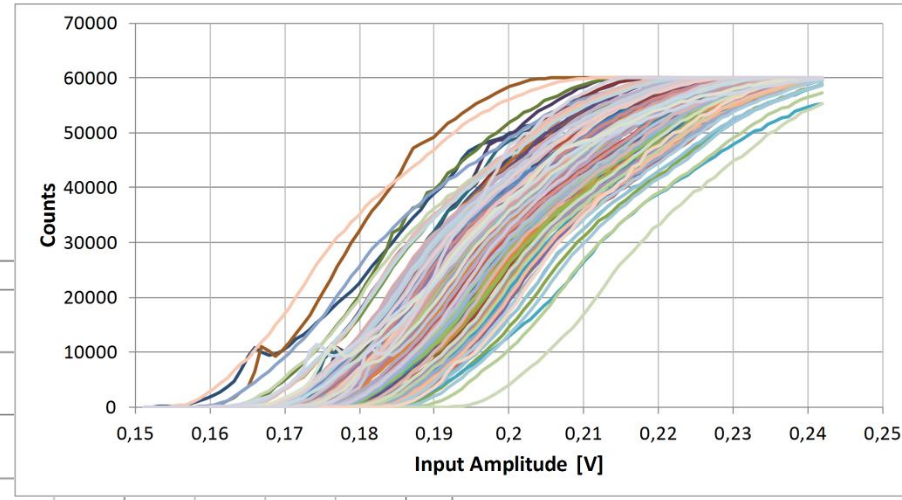


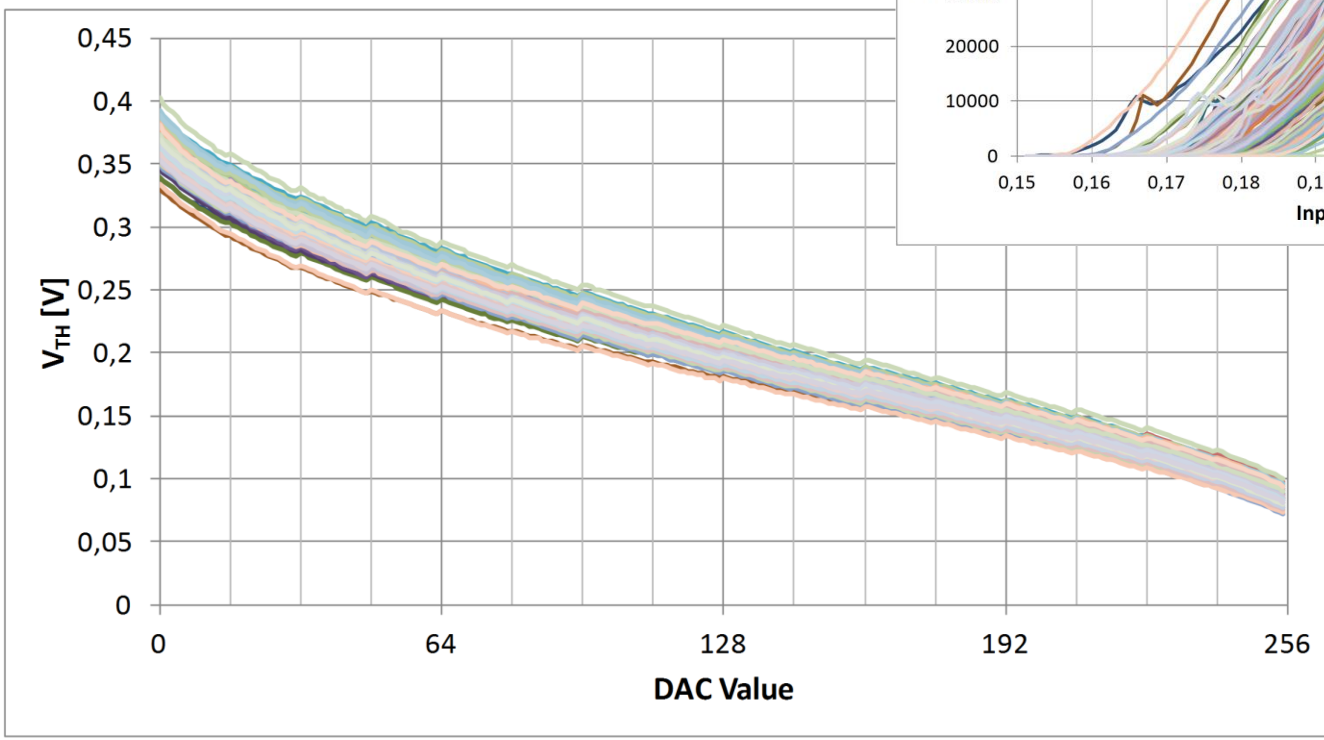


Correction DACs characterization

S-curves before correction:

σV_{TH} = 7.01 mV



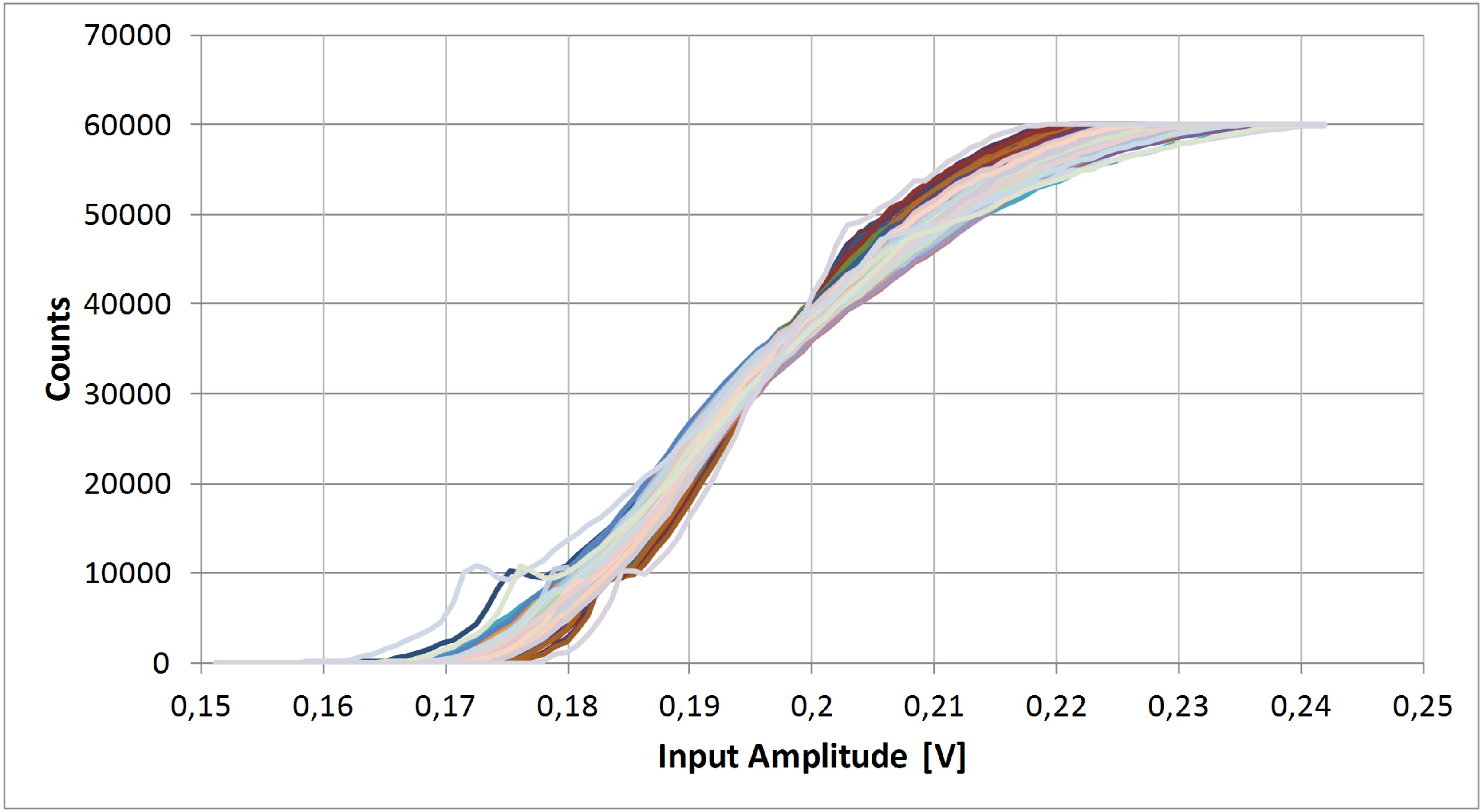


TRIM-DAC characteristic

Correction Range:

± 150 mV

Correction DACs characterization



S-curves after correction: $\boldsymbol{\sigma V_{TH} = 0.76\ mV}$

Read-out protocol
GBTx – protocol overview

K.28.1	NO_OP	K.28.1	WR_ADD	K.28.1	WR_DAT	K.28.1	RD_DAT

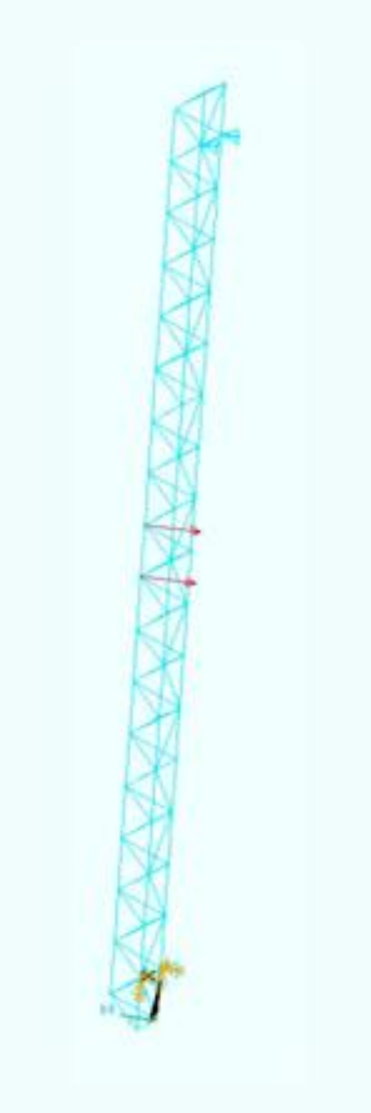
Downlink data:

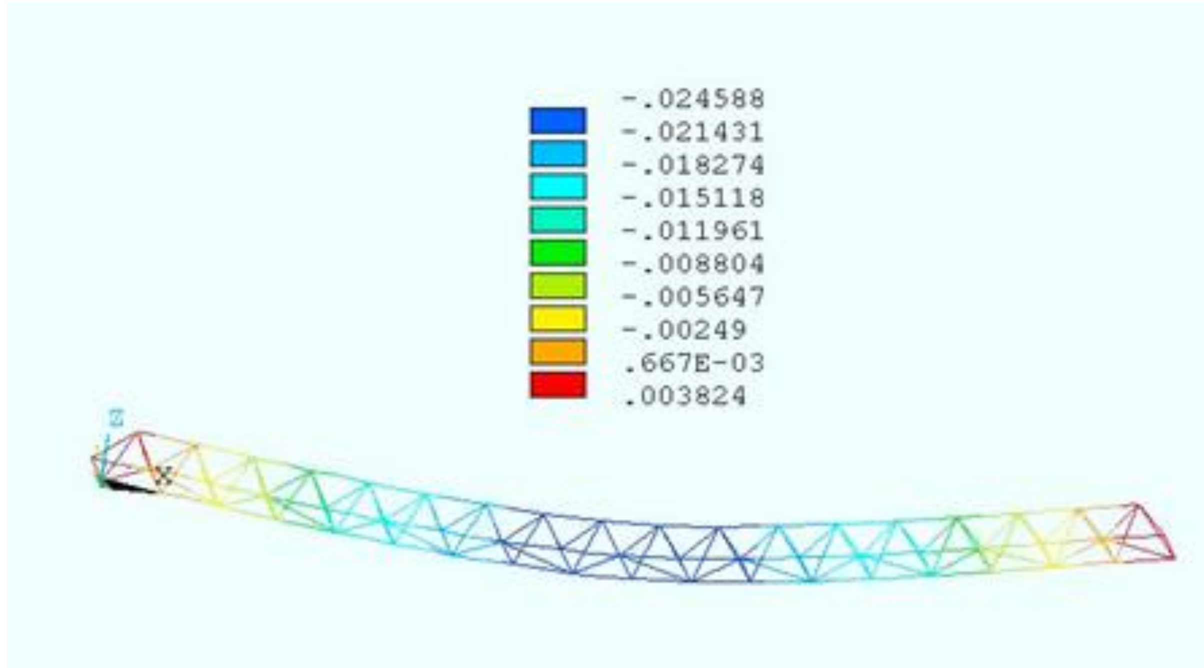
- Control requests
- 8b/10b encoding
- Deterministic latency by using: constant length frames, transmitted continuously
- Each 60-bit frame starts with K28.1 comma character, CRC protected

SYNC	DUMMY	HIT	TS_MSB	ACK	RD_ACK	DUMMY	SYNC

Uplink data:

- Hit data, control responses (6 types of frames)
- 8b/10b encoding
- Constant length frames (30-bit), transmitted continuously
- No CRC on Hits
- Periodic (rare) SYNC frames for link monitoring





	AGS	AGS	SPS	SPS	RHIC	RHIC	LHC	FAIR
Starting year	1986	1992	1986	1994	2000	2001	2008	2018
A_{max}	^{28}Si	^{197}Au	^{32}S	^{208}Pb	^{197}Au	^{197}Au	^{208}Pb	^{197}Au
$\sqrt{s_{NN}}$ $[GeV]$	5.4	4.7	19.2	17.2	130	200	5500	9