The CBM experiment at FAIR

– Overview of detector and technologies –

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GSI Helmholtzzentrum für Schwerionenforschung GmbH

Facility for Antiproton and Ion Research

Compressed Baryonic Matter Experiment

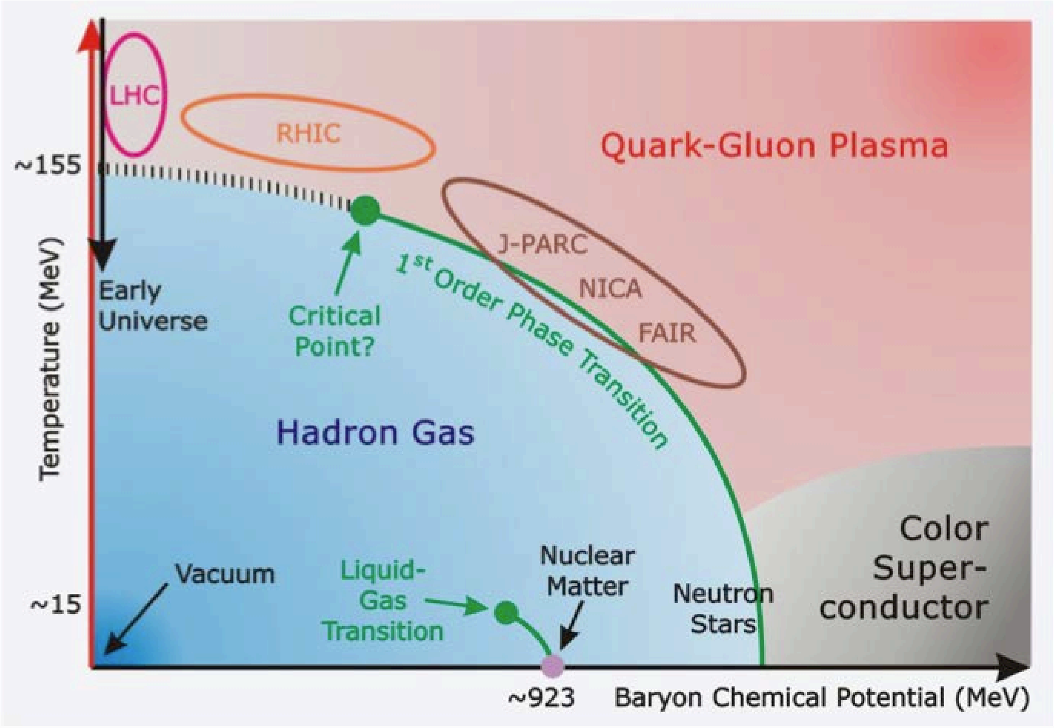
Outline

- *very brief reminder of the physics aim of CBM*
- *out of which the proposed experiment structure follows*
- *and the chosen detectors and technologies*
- *before we then overview those, a brief look at the status of FAIR and the site construction*
- *finally, a short selected look at the demonstrator setup mCBM is made*

… all sticking to a personal selection and depth of the matter, as the topics are quite extensive …

Physics aim

Systematic exploration of QCD matter at large baryon densities, with high accuracy and (rare) probes.



Equation-of-state, phases

- *Hadron yields, collective flow, correlations, fluctuations*
- *(Multi-)strange hyperons (K, Λ, Σ, Ξ, Ω)*
- *production at (sub)threshold energies*

Chiral symmetry

- *In-medium modifications of light vector mesons*
- *ρ, ω, φ → e^++e^- (μ^++μ^-) via dilepton measurements*

Hypernuclei

Charm production

- *Excitation function in p+A collisions (J/ψ, D^0, $D^\pm$)*
- *Charmonium suppression in cold nuclear matter*

Physics aim

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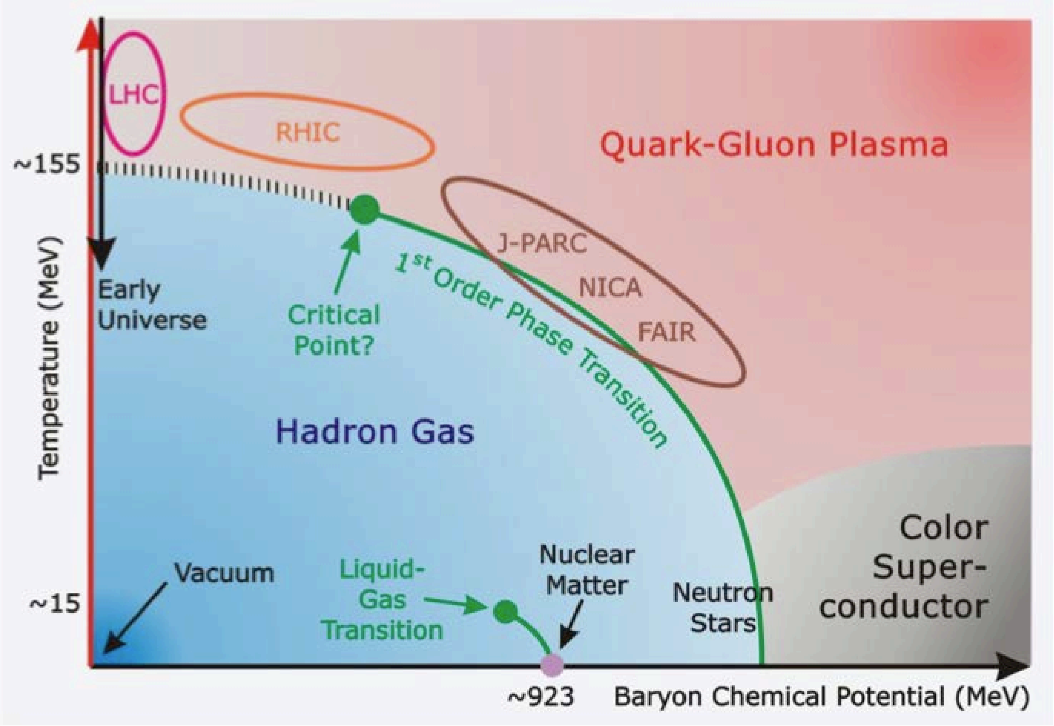
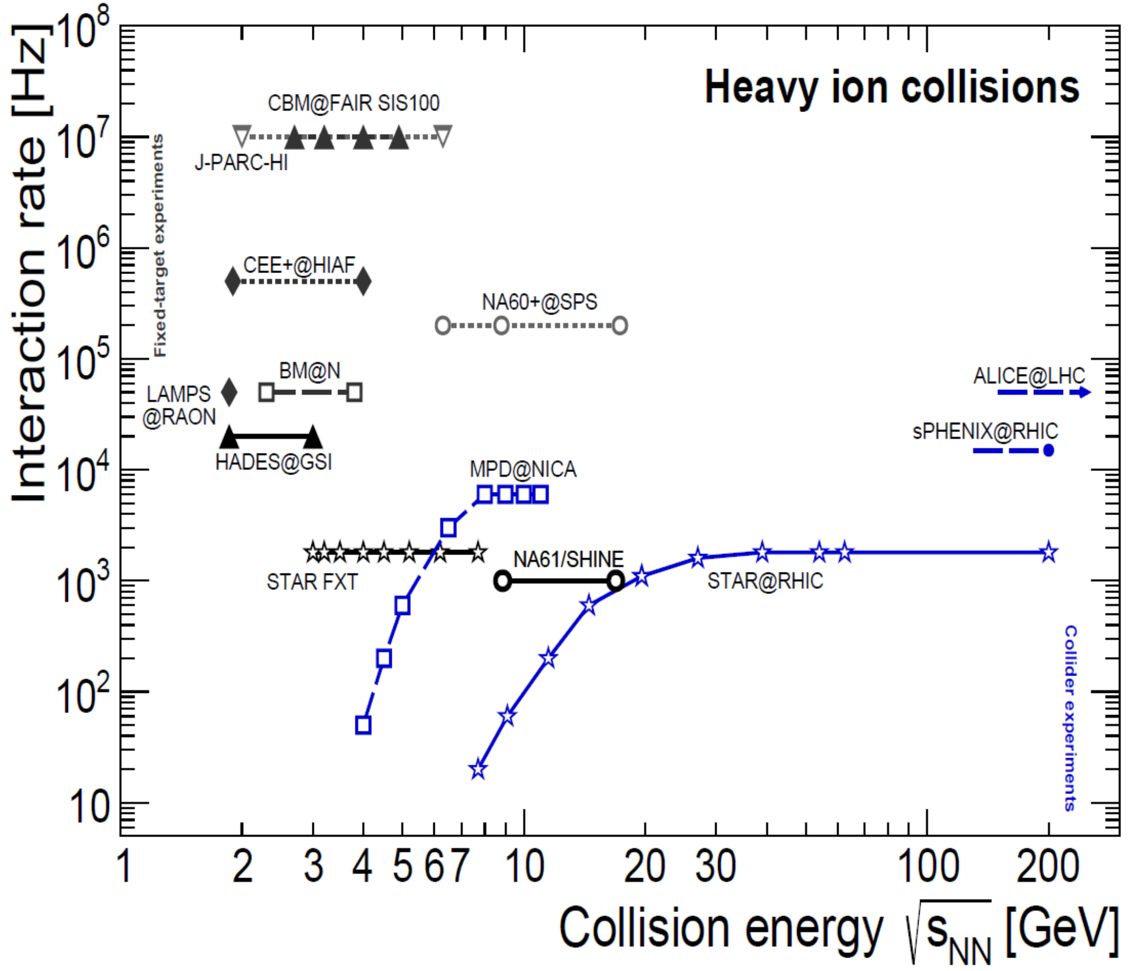


T. Galatyuk, https://github.com/tgalatyuk/interaction_rate_facilities, 2022



CBM and HADES experiments at SIS100

CBM

forward spectrometer

- *polar angular acceptance* $2.5^\circ < \Theta < 25^\circ$
- *full azimuthal coverage*

configurations:

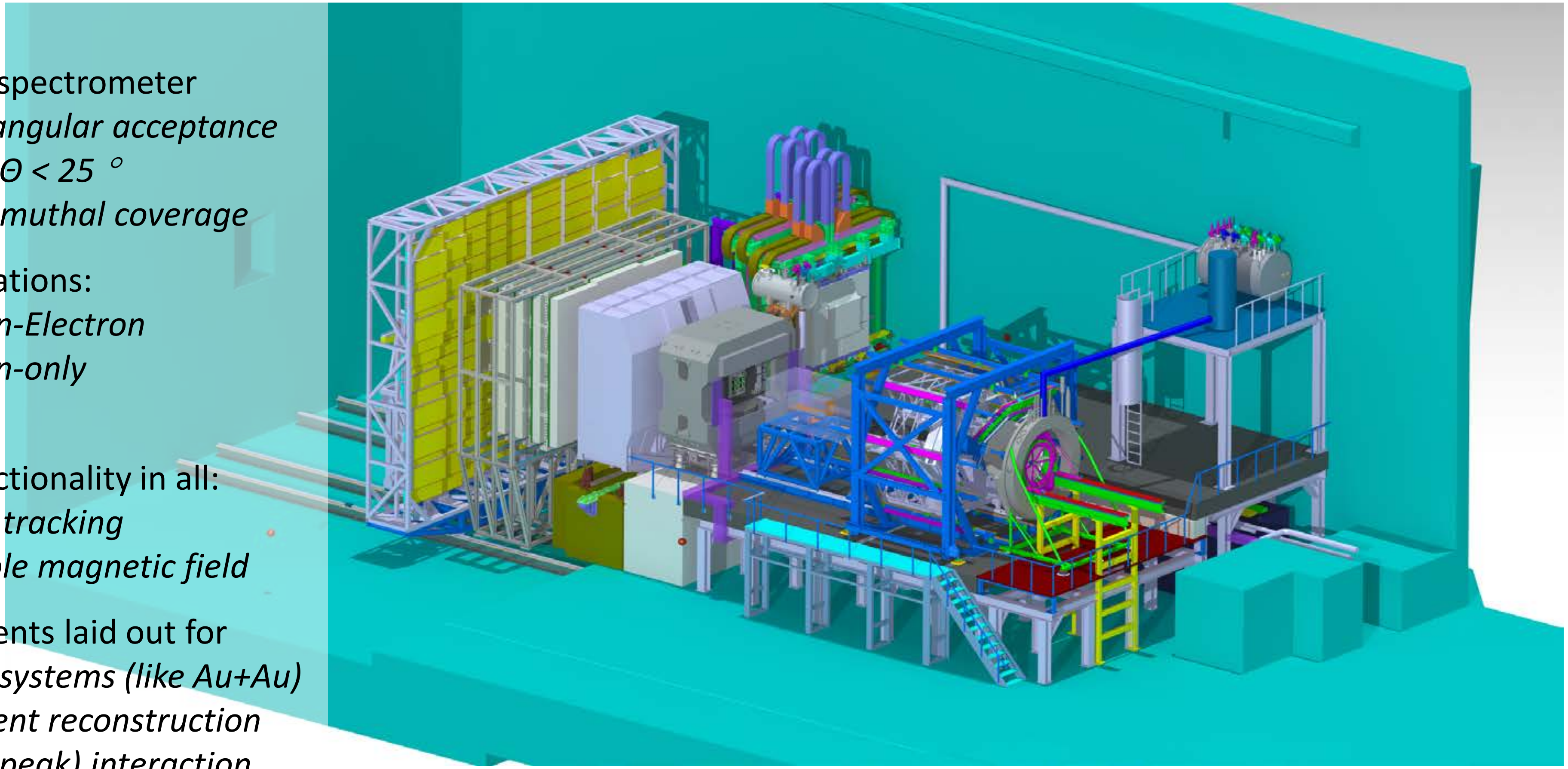
- *Hadron-Electron*
- *Hadron-only*
- *Muon*

core functionality in all:

- *silicon tracking in dipole magnetic field*

components laid out for

- *heavy systems (like Au+Au)*
- *full event reconstruction up to (peak) interaction rate 10^7/s*



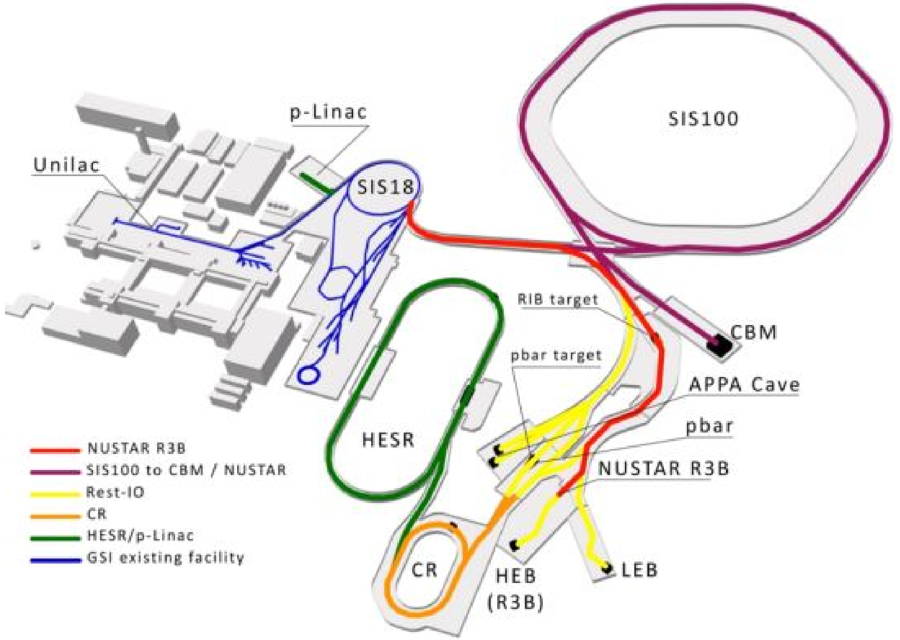
HADES *SIS18 → SIS100*

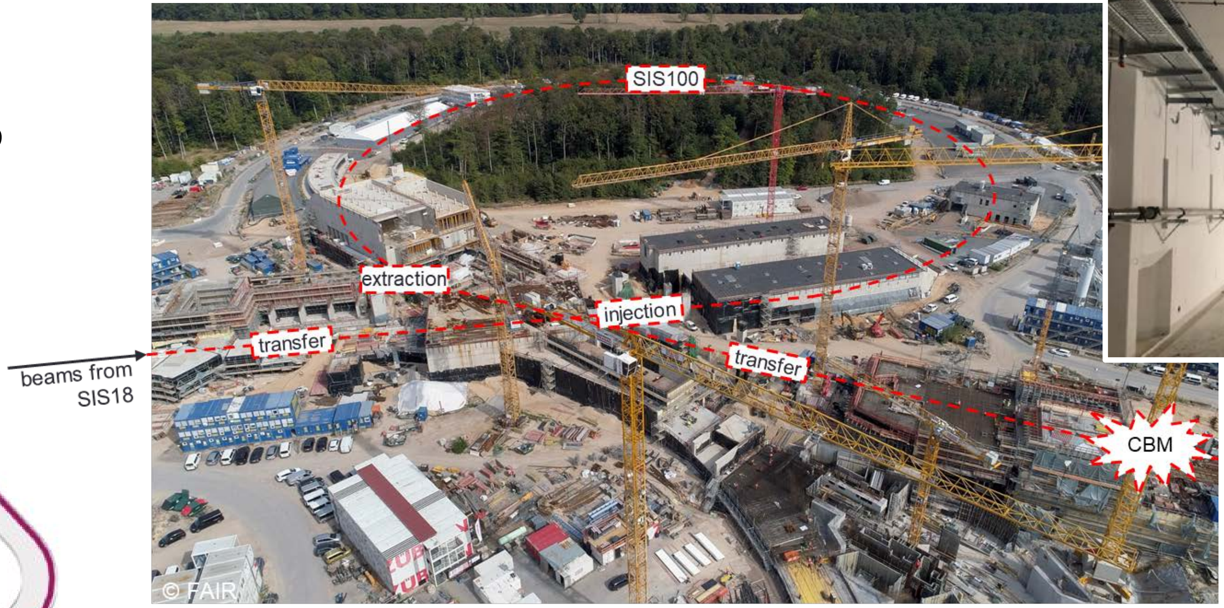
CBM-HADES

- sharing of same beamline
- different target positions
- different running times (HADES beam dump between CBM and HADES)

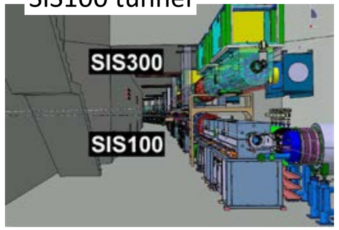
FAIR and CBM sites under construction

Fall 2022

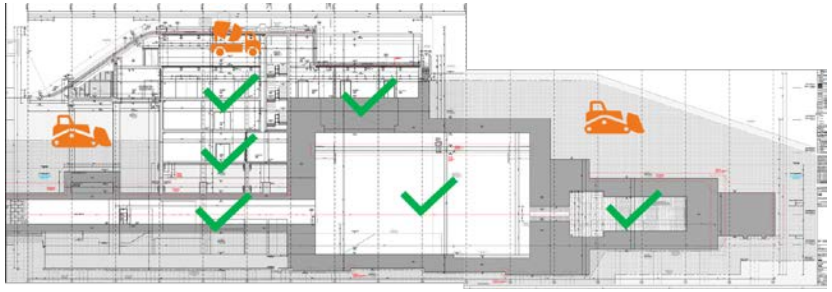




SIS100 tunnel



CBM cave



beams to CBM: $\sqrt{s_{NN}^{max}} = 4.9$ GeV
2-29 GeV (p), 2-14 AGeV (Ca), 2-11 AGeV (Au)
up to 10^9 ions/s on target

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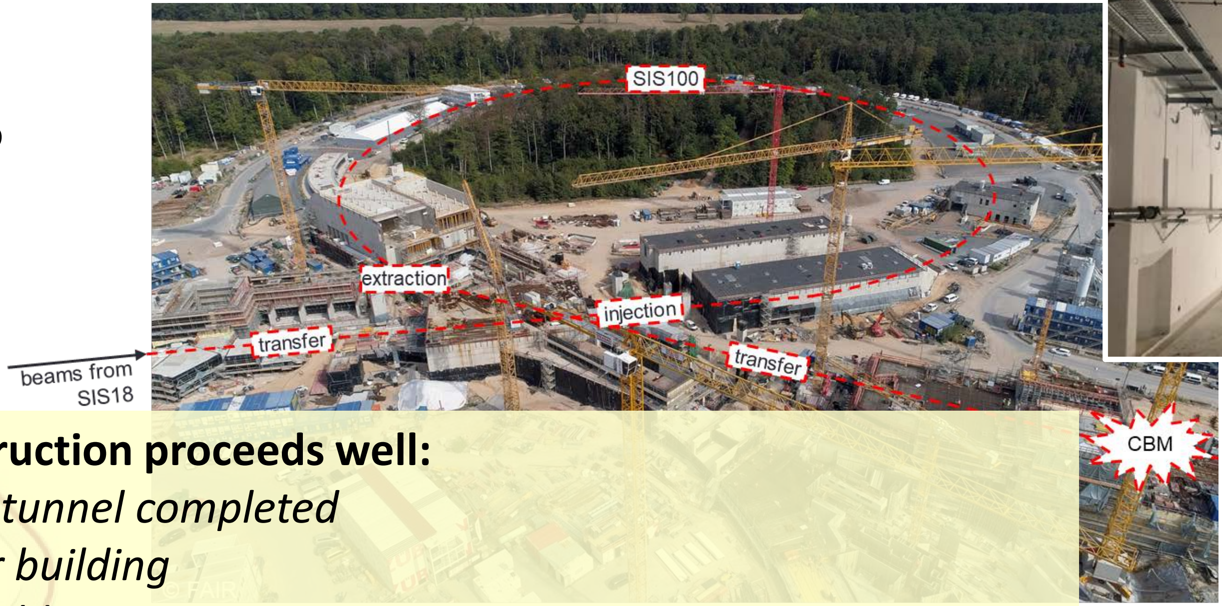

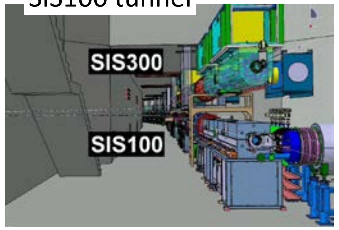

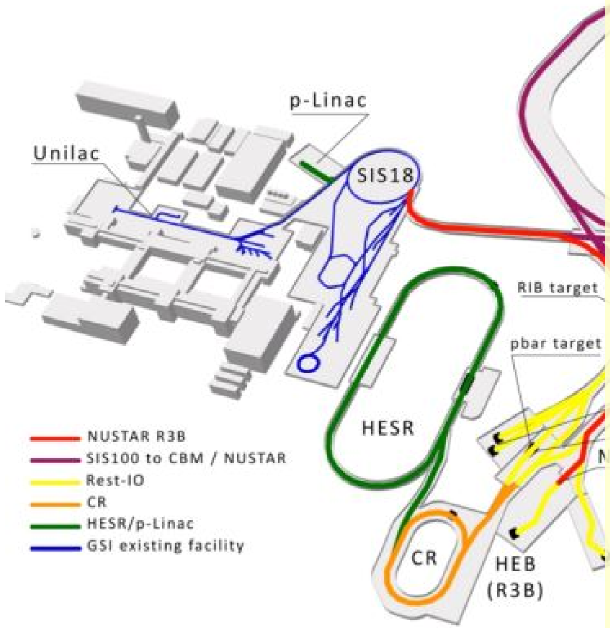

Civil construction proceeds well:

- *SIS 100 tunnel completed*
- *transfer building*
- *CBM building*
- *NUSTAR sites …*

further installations open

Accelerator components:

- *many available (SIS100 dipole magnets)*
- *others (quadrupoles, …) impacted by sanctions due to Russia's war on Ukraine*

News, next steps: Scientific Review report, FAIR Council 12/2022

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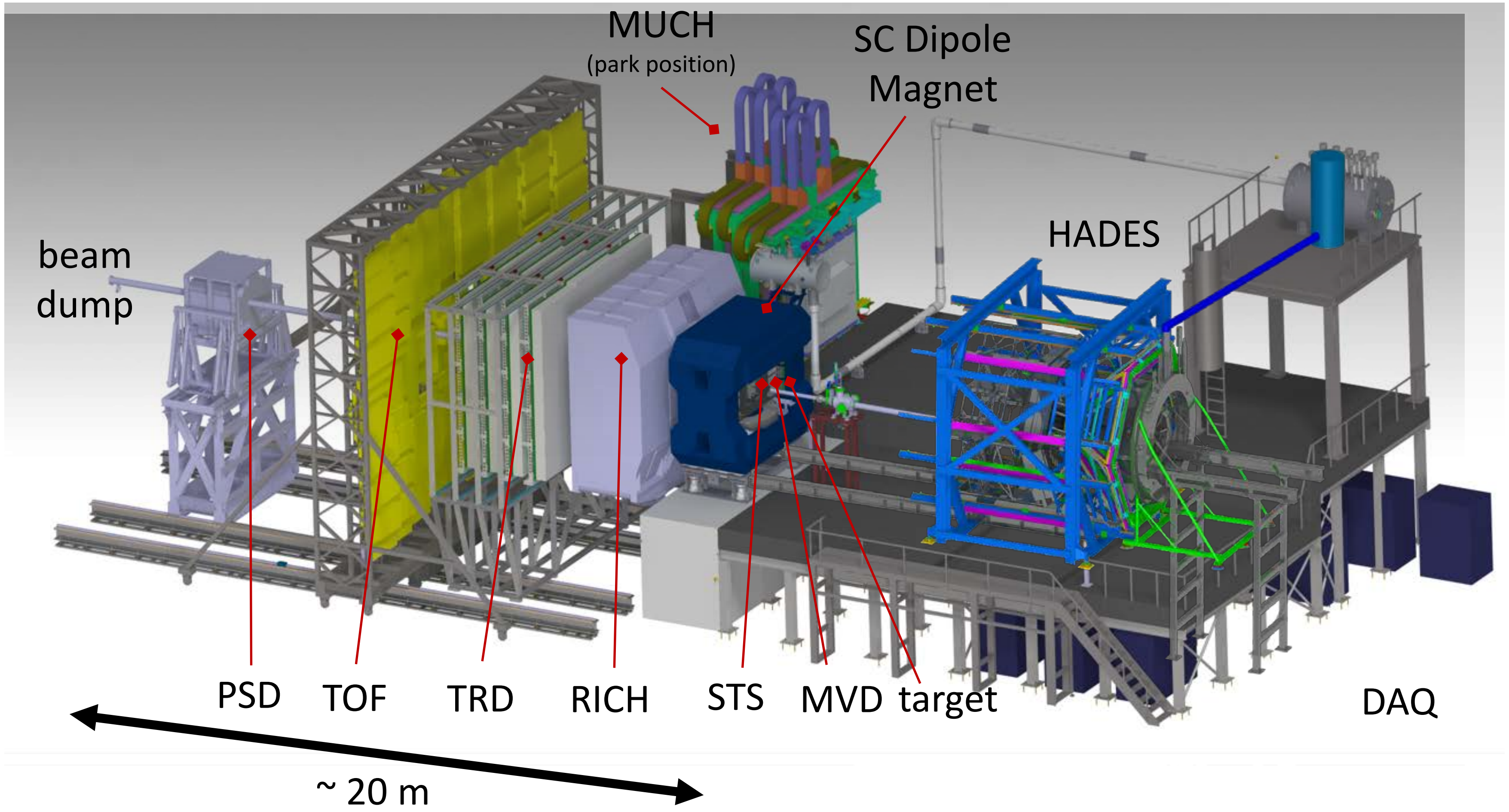
A walk through the detector systems

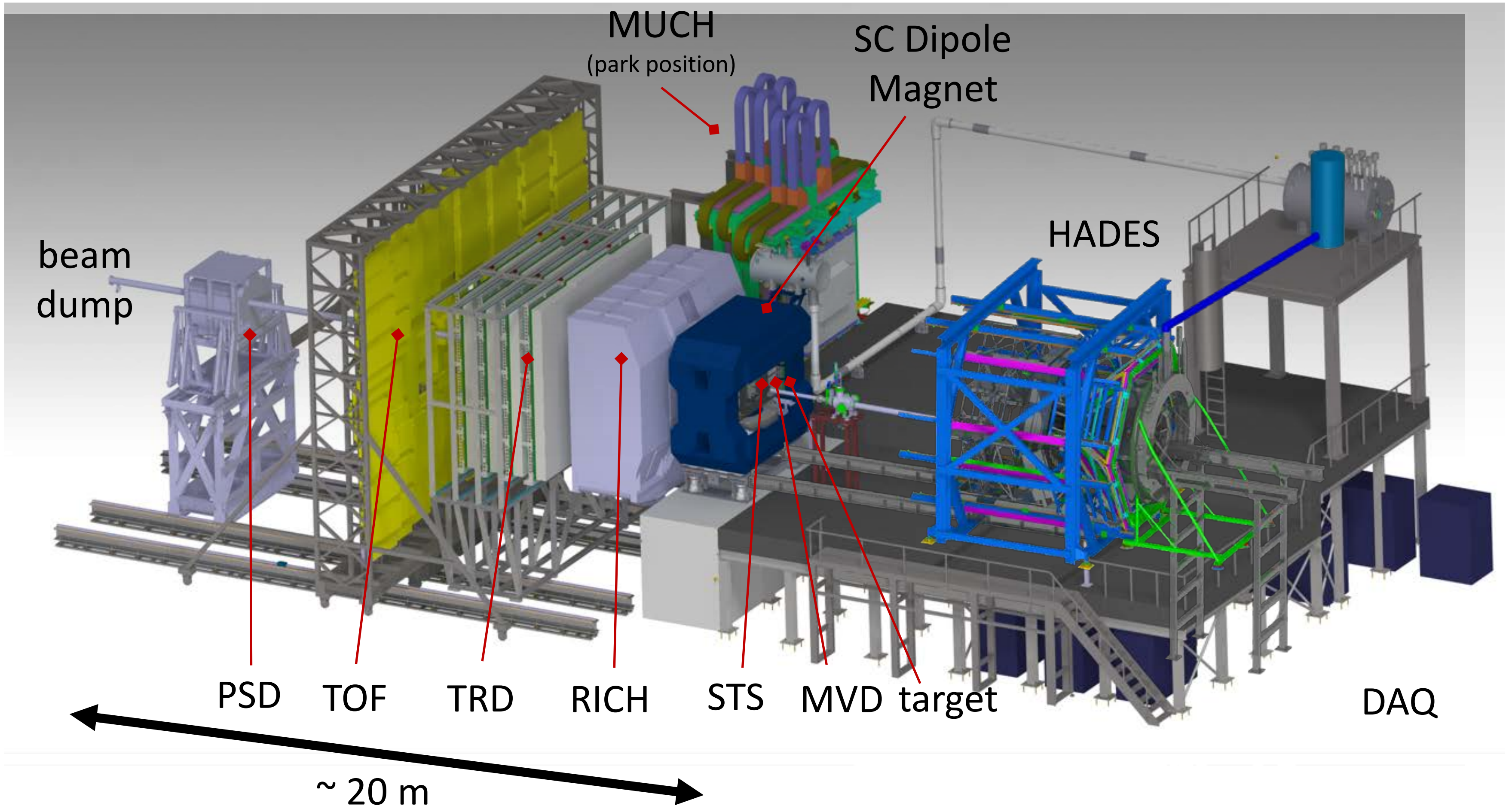


configurations:

- ***Hadron-Electron***
  MVD, STS, RICH, TRD, TOF, PSD
- *Hadron-only*
- *Muon*

Micro Vertex Detector (MVD)
Silicon Tracking Systen (STS)
Ring Imaging Cerenkov Counter (RICH)
Transistion Radiation Detector (TRD)
Muon Chambers (MUCH)
Time-of-Flight system (TOF)
Projectile Spectator Detector (PSD)
Data Acquisition System (DAQ)

A walk through the detector systems



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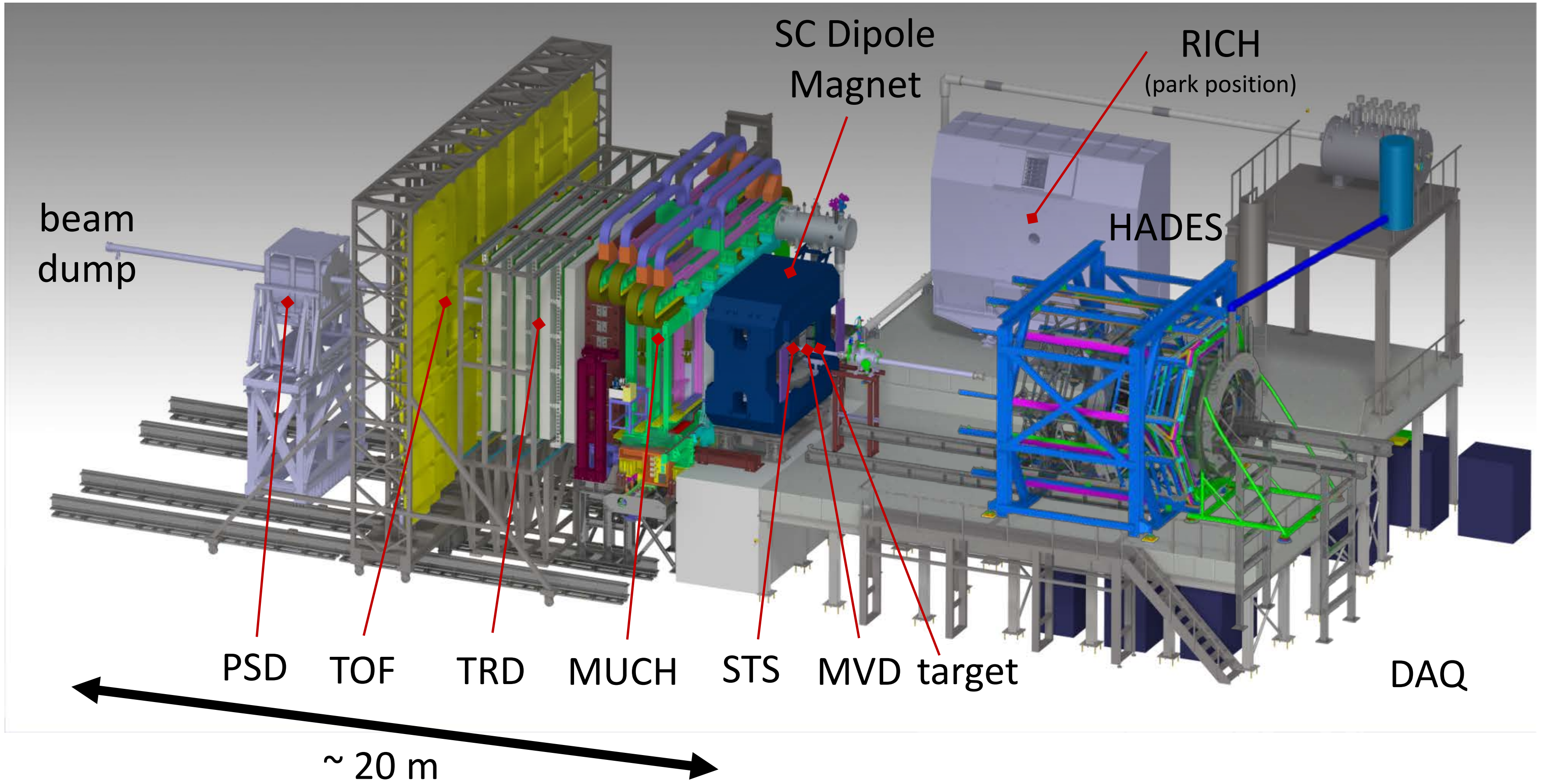

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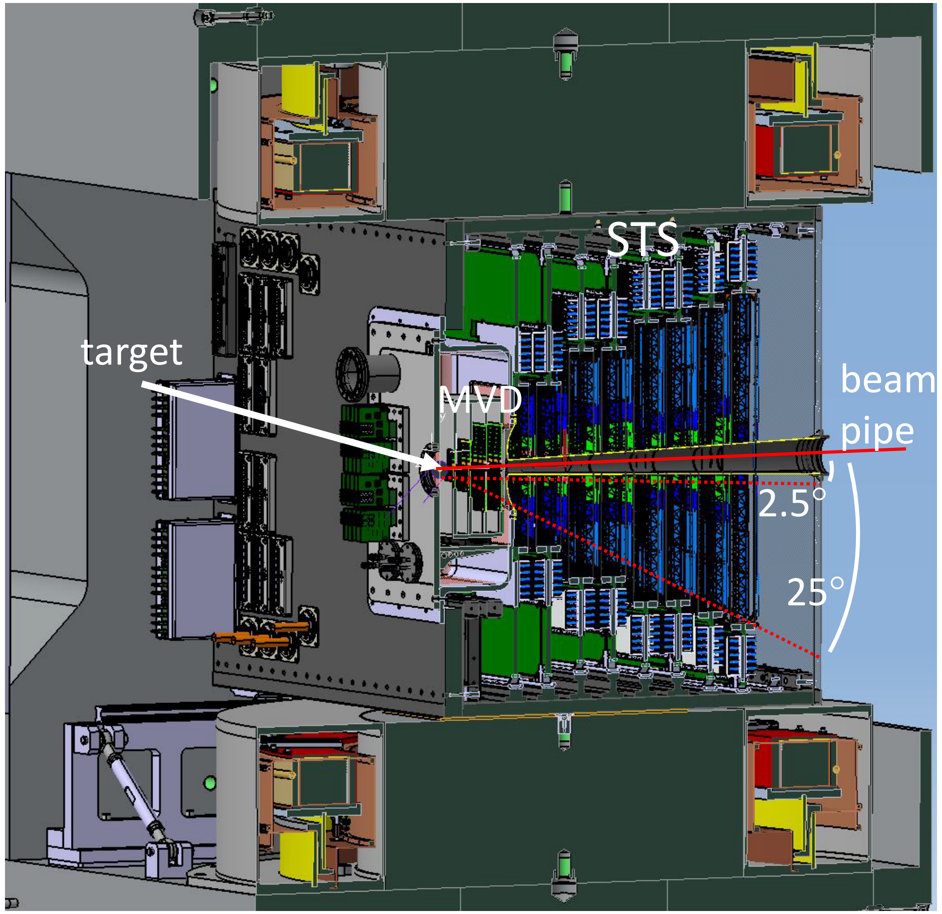
Silicon Tracking System

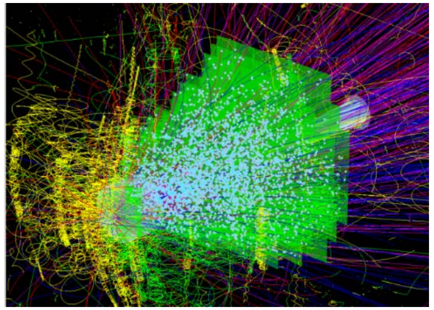


- Dipole magnet: H-shape, 320 t, warm iron yoke/poles, cylindrical super-conducting coils in two separate cryostats with LHe cooling
- opening: 144 cm (H), 300 cm (W), ≈ 120 cm (L)
- coils: Nb-Ti filaments in copper matrix; 1749 turns
- operating current 686 A, max. magnetic field in coils 3.25 T

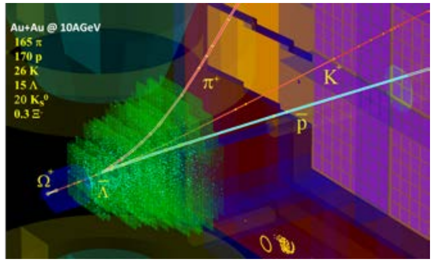
Main CBM detector for charged particle measurement incl. momentum determination.

- track point measurement in high-rate collision environment:
  $10^5 - 10^7$/s (A+A), up to 10^9/s (p+A)
- physics aperture, position in dipole magnet:
  - $\approx 2.5° \leq \Theta \leq 25°$, $0.2\ m \leq \Delta z \leq 1.1\ m$
  - first four stations wider for better low-momentum particle detection (e.g. di-lepton program)
- 8 tracking stations
  - radiation hard for several years of operation
  - double-sided silicon microstrip sensors
  - hit spatial resolution ≈ (x) 15 µm, (y) 110 µm
- self-triggering front-end electronics
  - time-stamp resolution ≈ 5 ns
- material budget: ≈ 0.3% – 1.5% X_0 per station
  - $\Delta p/p < 2\%$ (p > 1 GeV/c, 1 Tm field integral)

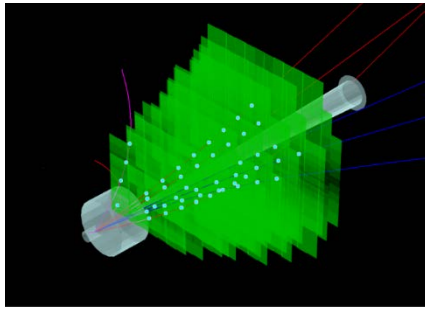
UrQMD + GEANT + CbmRoot



central Au+Au, 8 AGeV



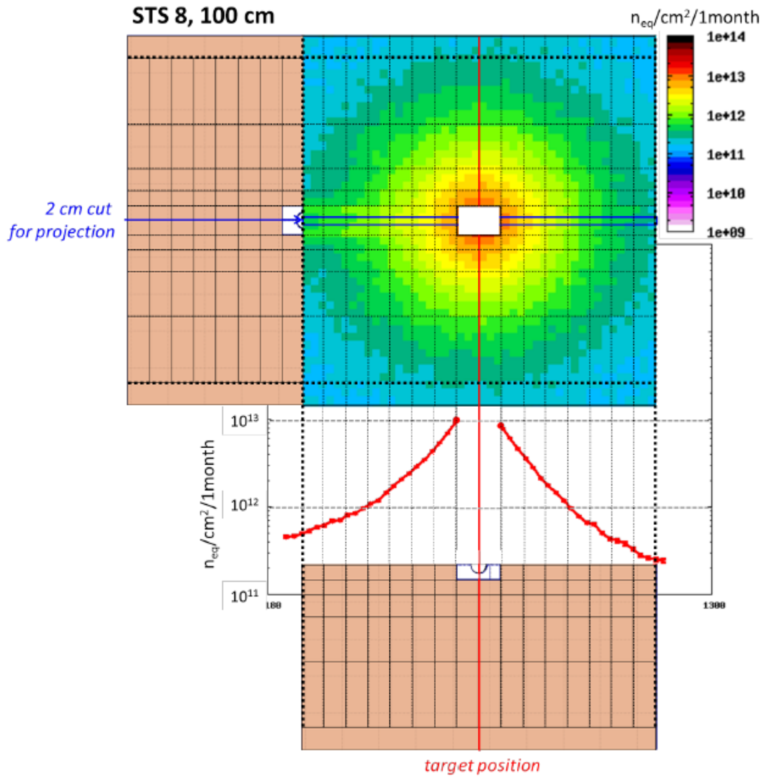
in-STS decay, Au+Au, 10 AGeV



p+C, 29 GeV

Environmental conditions for STS

Non-ionizing dose (FLUKA)

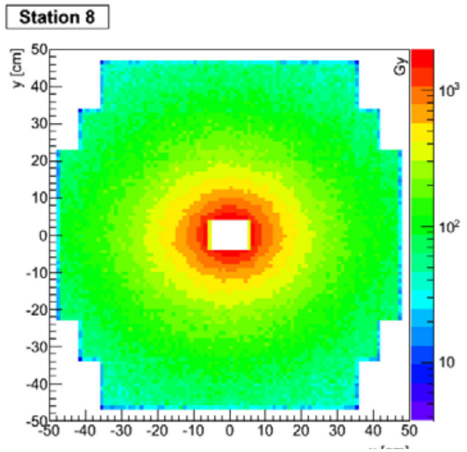


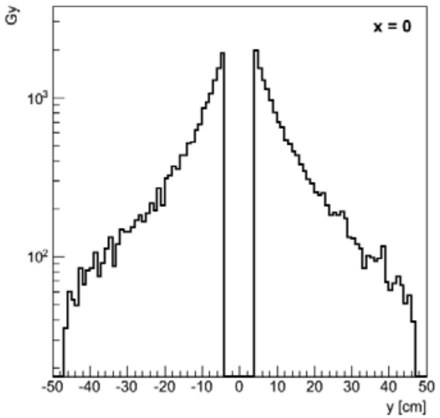
25 GeV/u Au+Au collisions; SIS300, CBM experiment in muon configuration.

1 month of "standard" running corresponds to 10^9 Au ions/s on a 250 µm Au target yielding 2.6×10^{13} interactions in its 1% nuclear interaction length.

Sensors:
< 10^{14} 1 MeV n_{eq}
over lifetime
→ **cooling to -10 °C**

Total ionizing dose (UrQMD/CBMRoot/GEANT3)





25 GeV/u Au+Au collisions; SIS300, CBM experiment in muon configuration.

5×10^{13} interactions;
Delta electrons produced at the target not included.

Electronics:
< 1 Mrad over lifetime
→ **locate at detector periphery**

STS breakdown

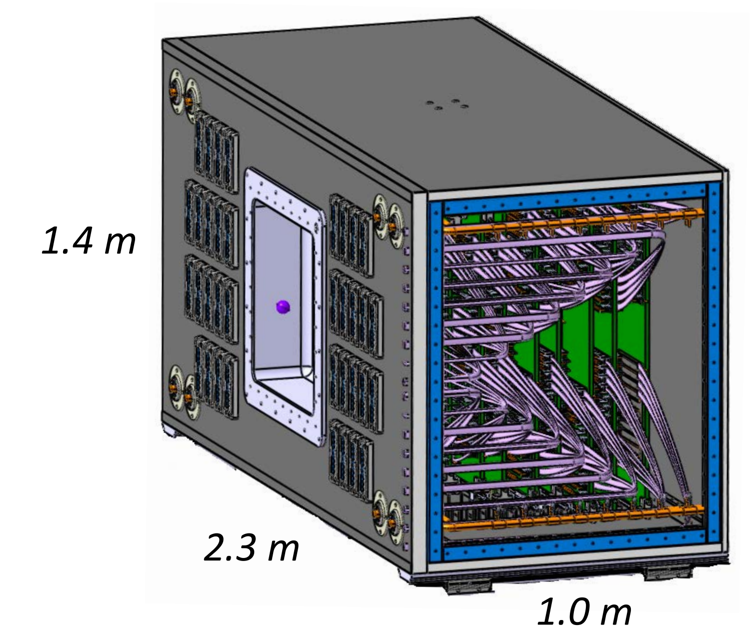
system integrated in thermal enclosure

sensors at T ~-10 °C (gas cooling)

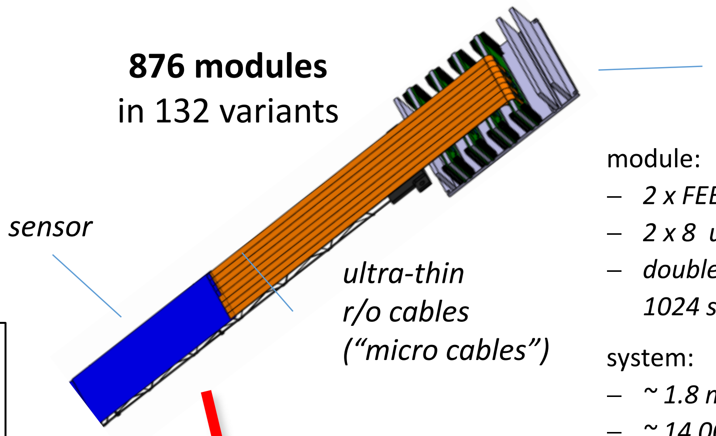
electronics cooling through thermal interfaces (liquid NOVEC, T > -40 °C)

services/ massive materials located at the periphery

includes target box, beam pipe

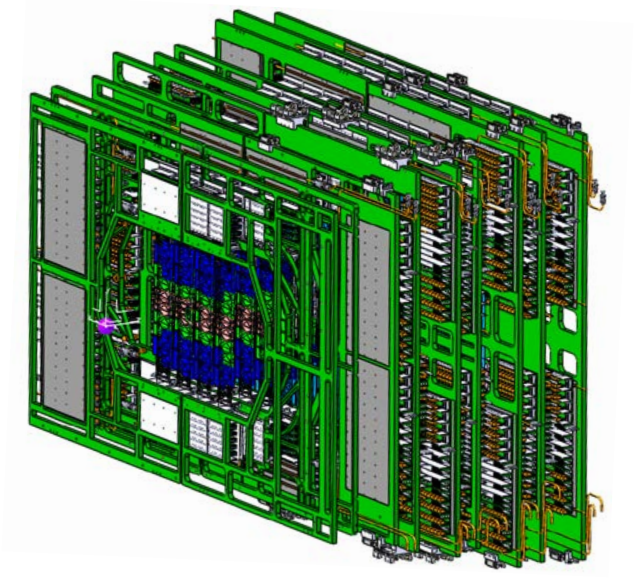


many components of unique design, precisely matching their specific location

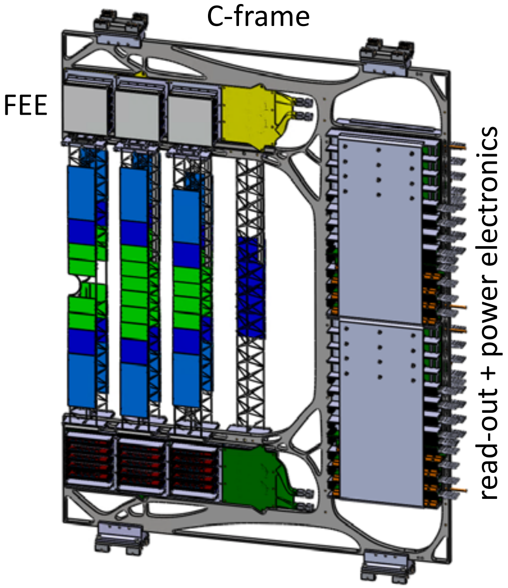


module:
- *2 x FEBs à 8 r/o ASICs/128 ch.*
- *2 x 8 ultra-thin read-out cable stacks*
- *double-sided silicon micro-strip sensor, 1024 strips per side*

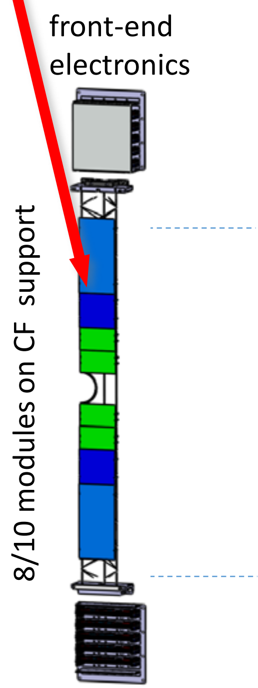
system:
- *~ 1.8 million read-out channels*
- *~ 14 000 r/o ASICs “STS-XYTER”*
- *~ 40 kW power dissipation incl. all r/o + power electronics*



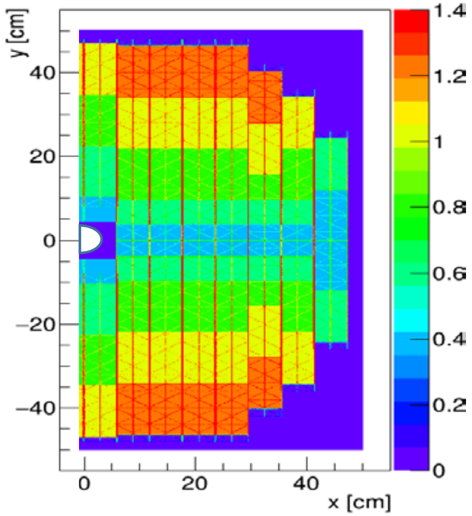
8 tracking stations



18 mechanical half-units



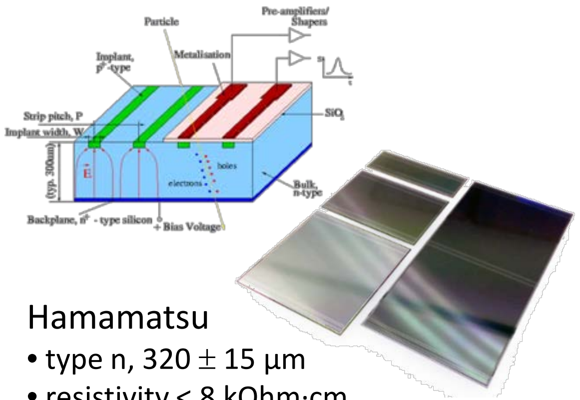
material budget/station [$\%X_0$]



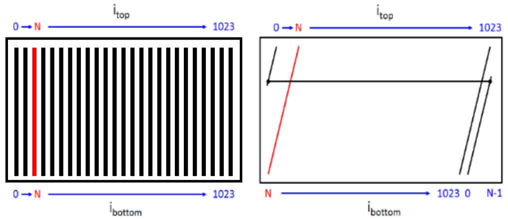
106 ladders in 41 variants

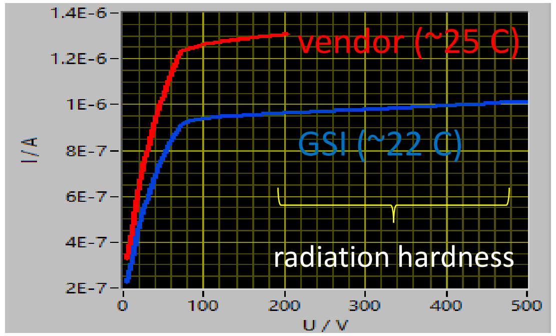
Sensor, FEE, microcables, assembly

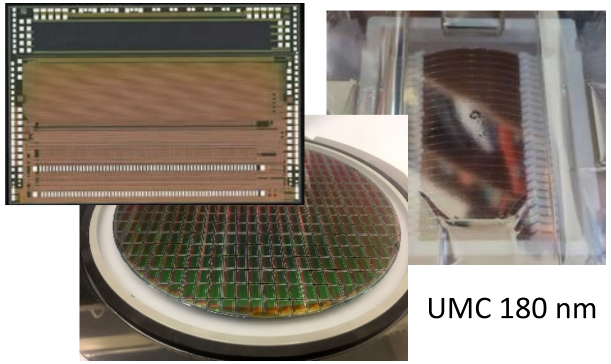
arXiv:1506.05168



Hamamatsu
- type n, 320 ± 15 µm
- resistivity < 8 kOhm·cm
- double-sided, 0/7.5° strip angle
- p-side with 2nd metal routing
- 1024 channels/side , 6 cm wide
- strip pitch 58 µm; AC read-out
- strip lengths: 2/4/6/12 cm



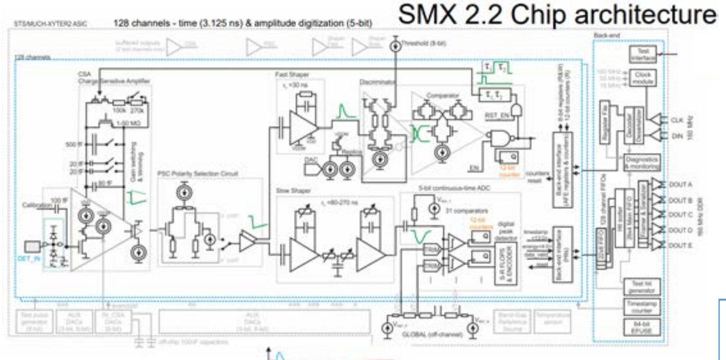




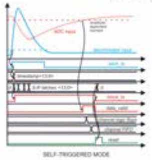
UMC 180 nm

SMX2.2, a 128 Channel, Event-Driven Tracking Chip for Silicon and Gaseous Detectors

SMX 2.2 Chip architecture

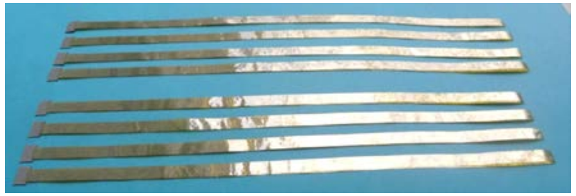


0-12 fC electrons & holes (STS)
gain switching & trimming
250 khit/s rate (pulsed reset)
80-280 ns shaping time (slow path)
time-walk corrected offline
continuous-time ADC + peak det.
P=8.5-10 mW/channel (incl. logic)

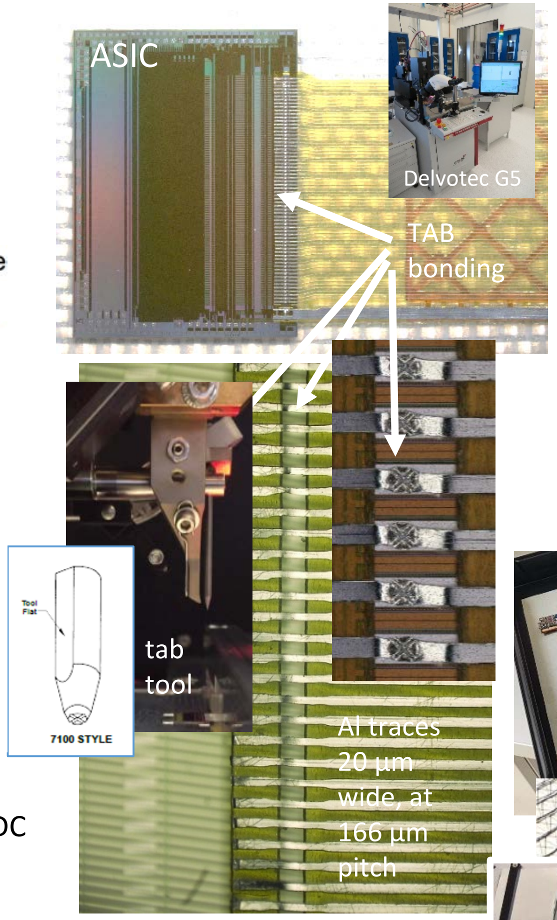


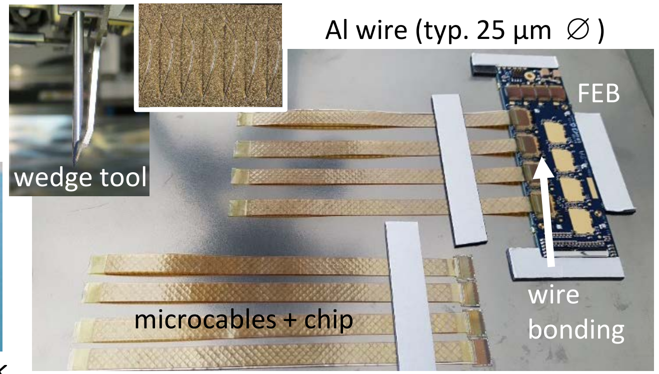
Back-end:
- control via synthesized reg & AFE DICE cells
- 9.41 – 47 Mhit/s/ASIC data BW
- dedicated protocol
- throttling, diagnostic features
- link loopback (multi-level)
- 64-bit e-fuse for traceability

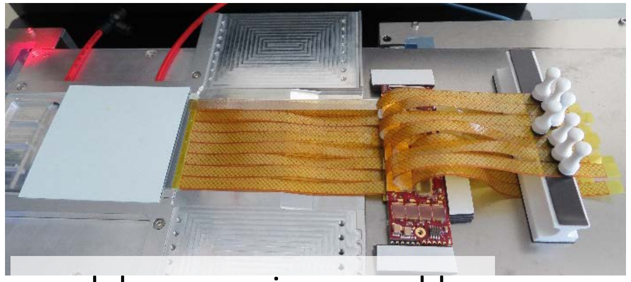
- fast path: timing 3.125 ns
- slow path: amplitude measurement 0-12 fC, 8bit ADC
- P=8.5-10 mW/channel (incl. logic)
- data rate: 9.41 – 47 Mhit/s/ASIC



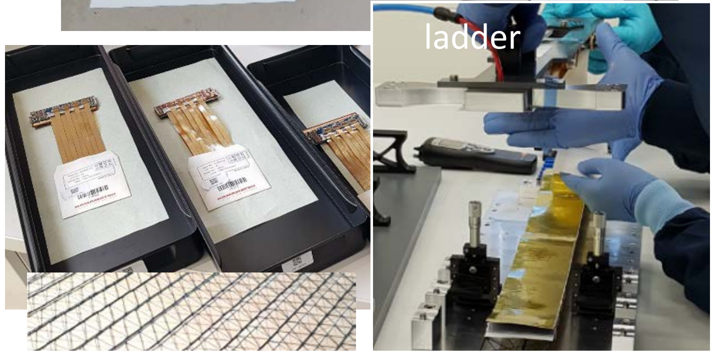
microcables: Al-polyimide, 2× 14+10 µm thick

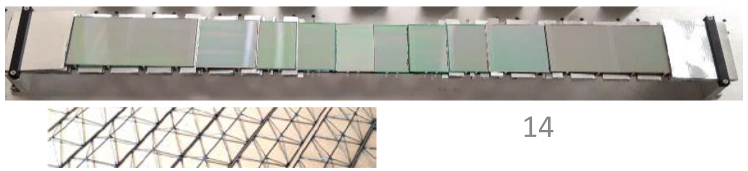




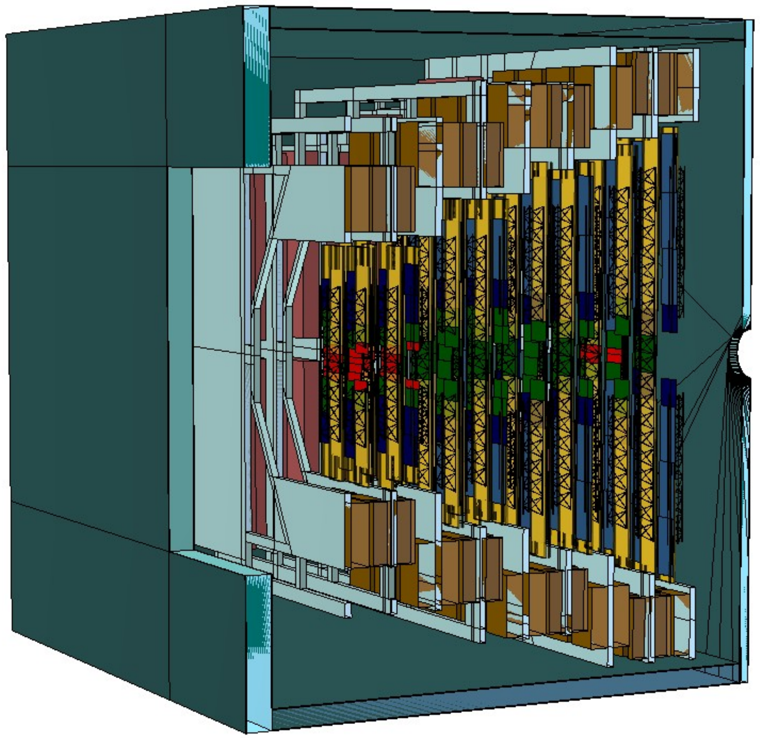


module, pre-series assembly



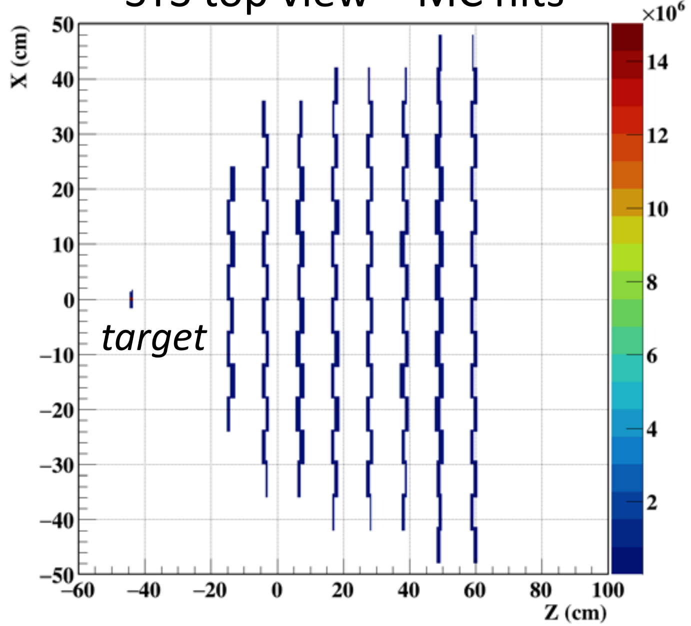


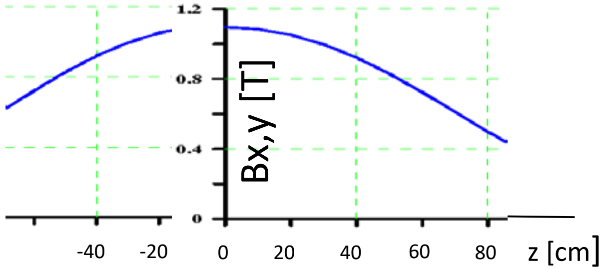
STS – performance simulations



GEANT model with active and passive materials (v21e)

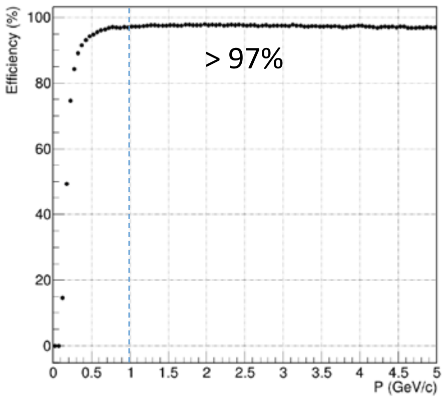
STS top view – MC hits





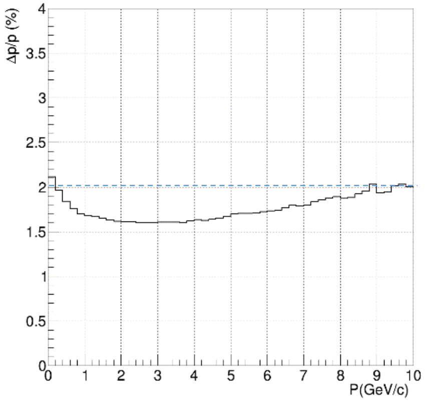
position in magnetic field

primary-track efficiency



Au+Au, 12 AGeV/c, 1 T

momentum resolution



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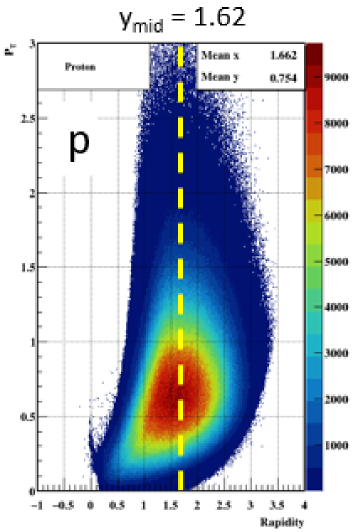
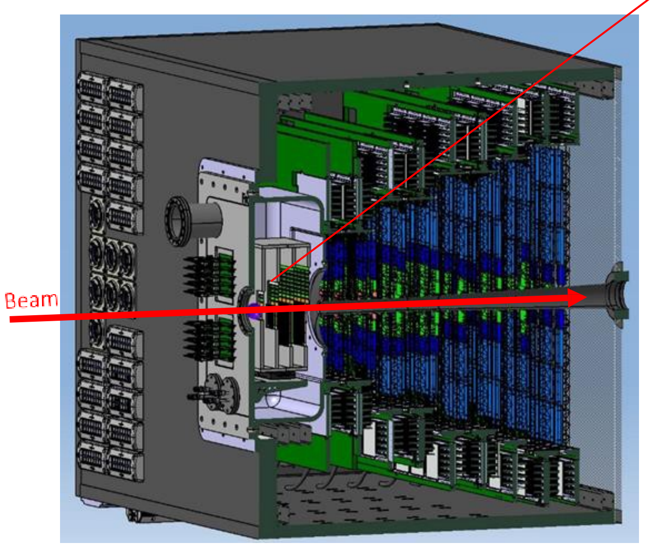


$p_T – y$ coverage

Micro Vertex Detector

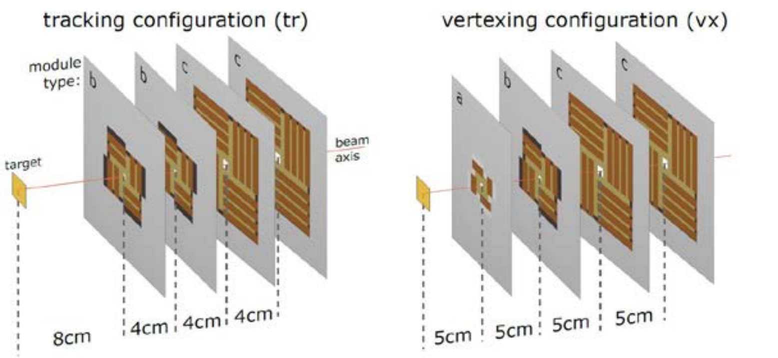
Monolithic Active Pixel Sensors
operating in target box vacuum ~ 10^{-4} mbar

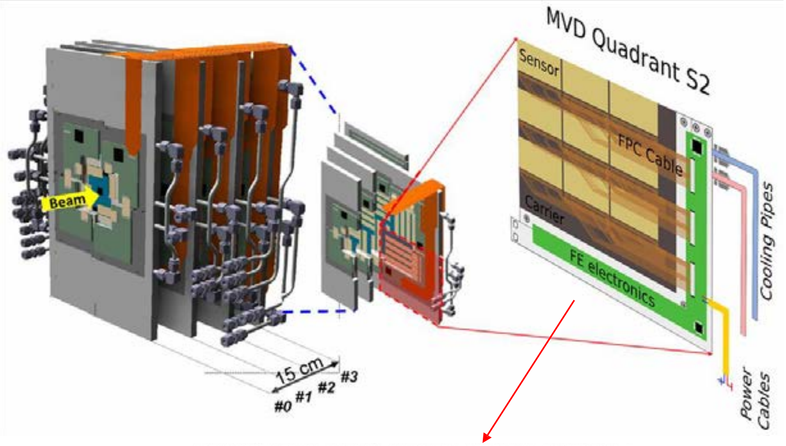
- *extends momentum reconstruction for charged particles down to about 300 MeV/c*
- *enables secondary vertex reconstruction for weak decays of charmed hadrons, precision significantly better than 100 µm for decay products with p_{lab} > 1 GeV/c, benchmarked by the D mesons (lab) life time.*

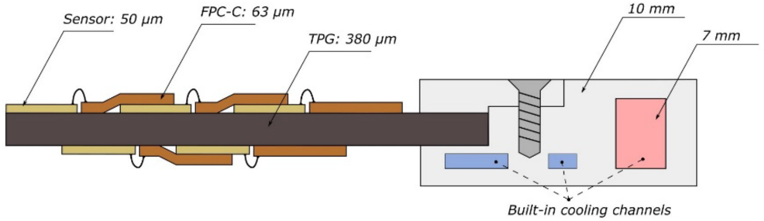


- ~300 CMOS sensor chips

- Material budget:
  - *O(0.5 %) (x/X0) /station*
  - *First station in VX: O(0.3 %) (x/X0)*

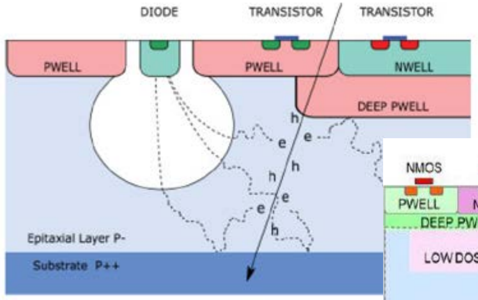






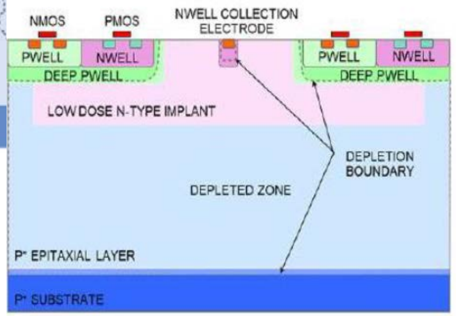
MIMOSIS 1: full-scale prototype

state-of-the-art MAPS technology



from standard MAPS

to modified with gap



Parameter	Value	
Technology	TowerJazz CIS 180 nm	
Epitaxial layer	~ 25 µm thick, > 1kΩ·cm	
Sensor thickness	300 µm or 60 µm	
Pixel size	26.9 µm × 30.2 µm	≈ 5 µm
Pixel array	1024 × 504 pixels	spat. resol.
Array readout time	≈ 5 µs	→ ~ 10^5coll./s
Power consumption	< 100 mW/cm^2	≈ 150 W total
Radiation hardness	> 7 × 10^{13} n/cm^2, > 1 Mrad (back/top biasing)	
Operation temperature	-10 C → liquid NOVEC cooling	

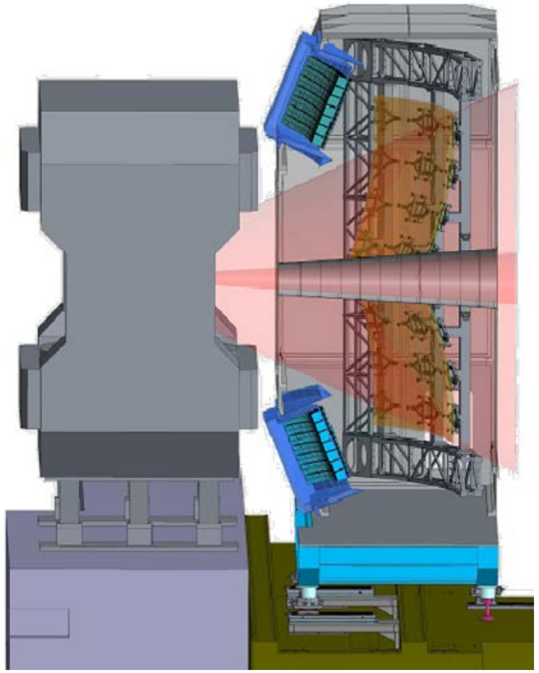
Station geometry	Inner radius (mm)	Active area (cm²)	no. of sensors front+back side	Module carrier dimensions (mm²)	Carrier material
a	5.4	33.0	4+4	51.0 × 59.6	CVDD
b	5.4	130.6	16+16	81.9 × 85.7	CVDD/TPG
c	10.4	455.1	64+48	124.9 × 143.9	TPG

CVD diamond / TPG carrier for heat evacuation to heat sink

Ring Imaging Cherenkov Detector

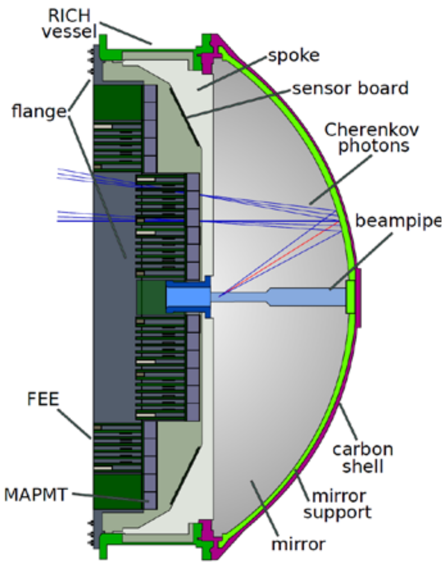
- Cherenkov Radiation: Charged particle travelling faster than speed of light in the respective medium radiates light at $\text{Cos}(\Theta) = 1/(n\,\beta) = v_l/v_p$ → threshold Cherenkov
- emitted light may be focussed onto a circle with $r_{circ} \sim \text{Cos}(\Theta) \sim 1/v_p$
- RICH signature + momentum reveals particle type

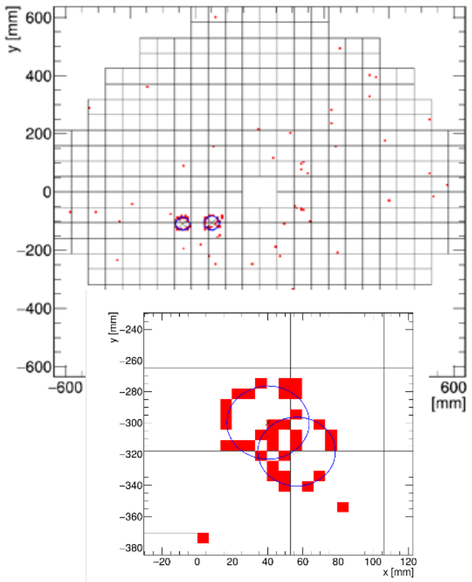
→ di-electron + hadron programs

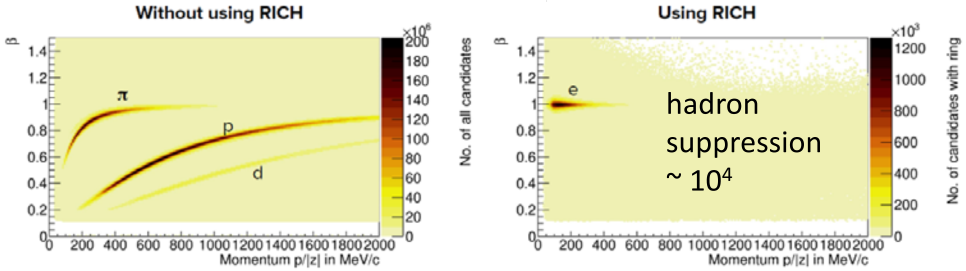


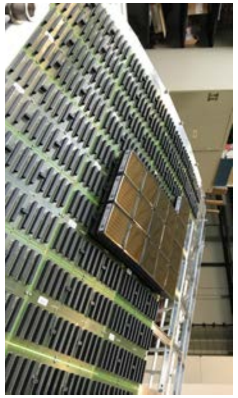
- CO_2 radiator gas, vessel volume $2.2 \times 6 \times 5.06\ m^3$ (l × w × h) = $67\ m^3$
  - *p-threshold 4.65 GeV/c, n=1.00045, UV cutoff 180 nm*
- 13 m^2 segmented glass mirrors with reflective Al and protective MgF_2 coating 80 tiles, 6 mm thick, R=3m, focal length 1.5m
- photo detector planes:
  - *MAPMT (H12700) readout (1000 pcs), 64k ch,*
  - *DIRICH readout chain: quasi free-streaming FPGA-TDC readout, leading trailing + edge time measurement*
- special challenge: B-shield down to 2-3 mT

CBM MAPMTs in HADES RICH

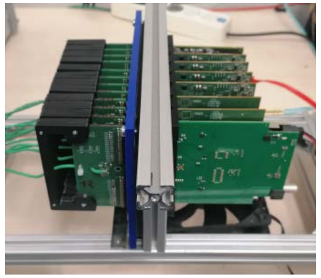








DIRICH readout modules

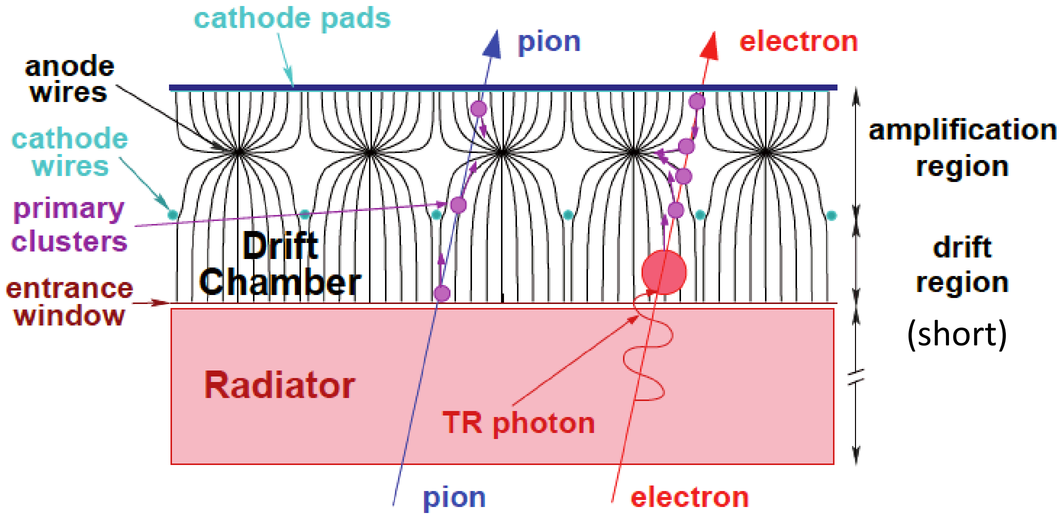


Transition Radiation Detector

Sudden change of ratio: $\vec{v}/c_{ph} = \vec{v}\, n/c$
⇒ emission of e.m. radiation ⇒ change of n: TR

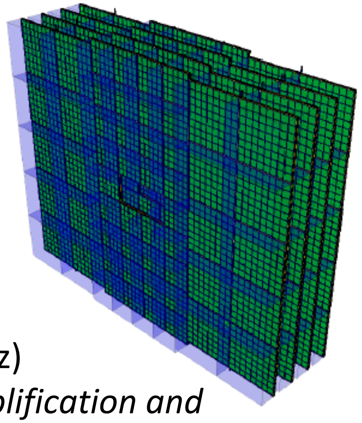
electrons: dE/dx + TR
rest (pions): dE/dx

counting gas mixture:
- Xe/CO2 (85/15) (optionally Ar/CO2 (80/20)
- high absorption cross section for photons in the TR spectral range



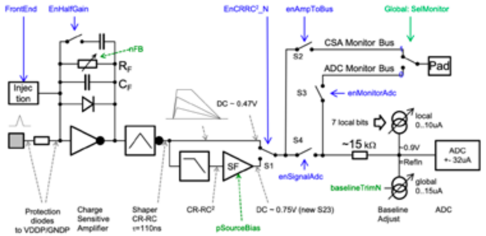
- electron identification at high momenta ($p \gtrsim 6$ GeV/c) where RICH alone is not longer effective
  → pion suppression factor of 10 – 20 (SIS100)
  → RICH + TRD (+ TOF): > O(10^4)

- identification of fragments (e.g. d ⟷ ^{4}He) via specific energy loss measurement (dE/dx)
  → resolution ~30 %

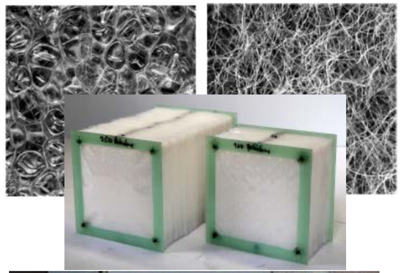


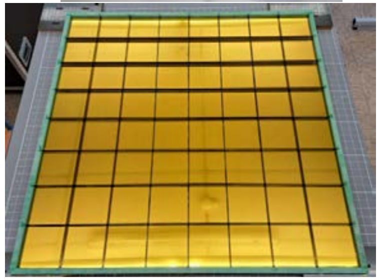
- four-layer TRD adds tracking capability:
  – Tracking between STS and TOF detectors
    → good space point resolution of ~ 300 µm
  – Works at high interaction rates (up to 10 MHz)
    → r/o ASIC SPADIC *(Self-triggered Pulse Amplification and Digitization ASIC)*

Module type	# Modules/plane	# Pads	Pad area (cm^2)
1	10	25,600	1.2
3	24	15,360	4.6
5	8	27,648	2.7
7	12	13,824	8.0
Total for one TRD layer	54	82,432	



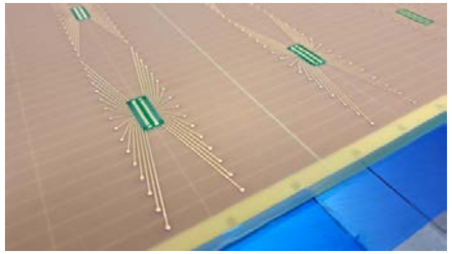
PE foam/ fibers/ foils





entrance window

25 µm Kapton + 50 nm Al
– Al coating is drift cathode, also moisture barrier
– TR absorption trough Al, 5 keV in 50 nm Al: 99,7% transmission

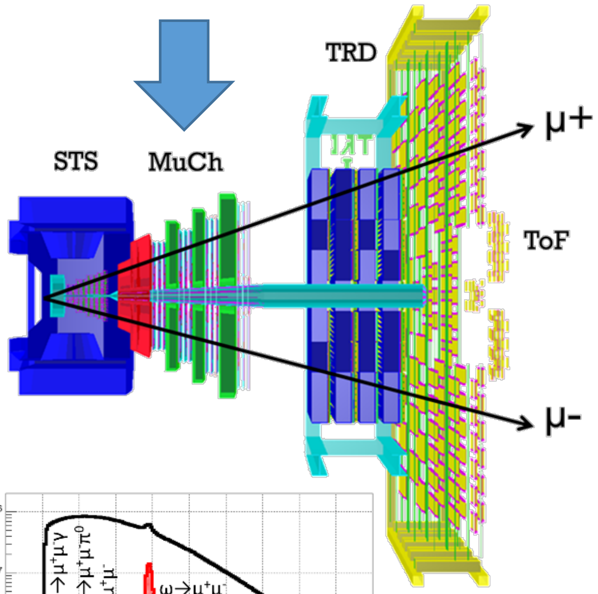


cathode pad plane

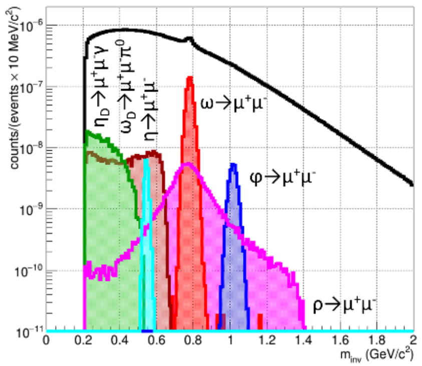
pads read-out by independent channels
TRD2D variant demonstrated: *triangular* pad read-out and *paired* signal amplification

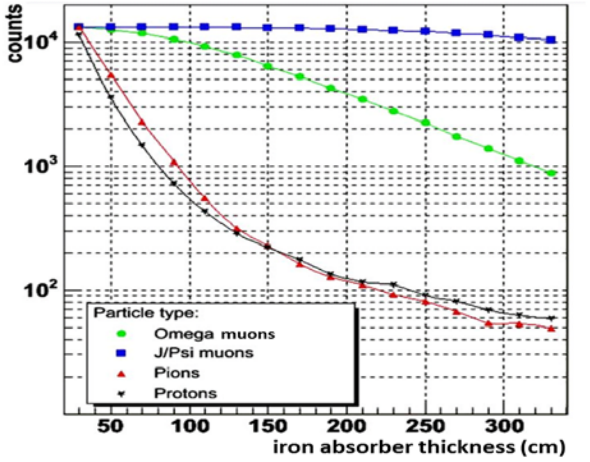
mTRD demonstrator

Muon Chambers



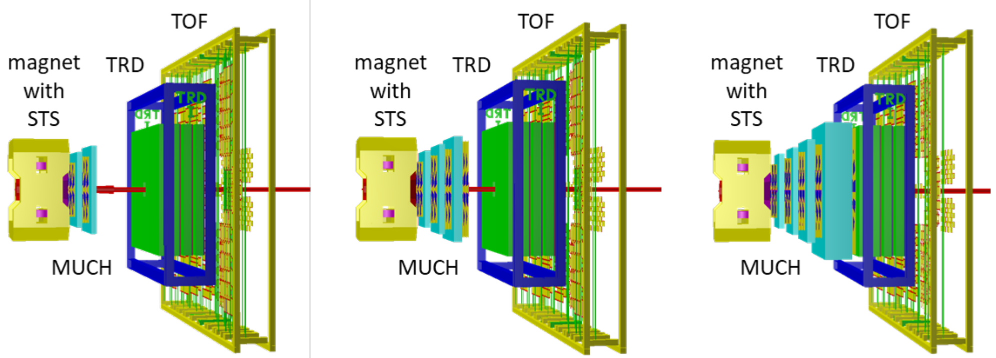
- instrumented hadron absorber
- muon: heavy lepton, mass 106 MeV
  - little multiple scattering + Bremsstrahlung
  - very long absorption length in matter
- separate muons from hadronic (strongly interacting) background
- energy dependence → energy filter for Muons





beam energies
above 4 AGeV for Au beam

low beam energies (up to 4 AGeV for Au beam)	low invariant mass region	intermediate and high invariant mass regions

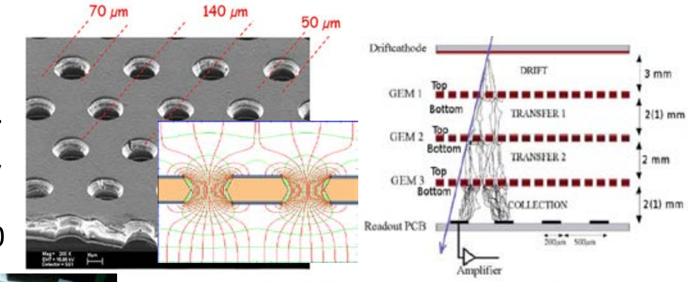


MUCH:	MUCH:	MUCH:
2 GEM stations	2 GEM + 2 RPC stations	2 GEM + 2 RPC stations
absorbers:	absorbers:	absorbers:
58 cm C + concrete	58 cm C + concrete	58 cm C + concrete
(20+20) cm Fe	(20+20+30) cm Fe	(20+20+30+100) cm Fe

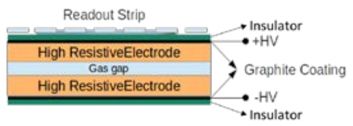
Each station with three tracking layers.

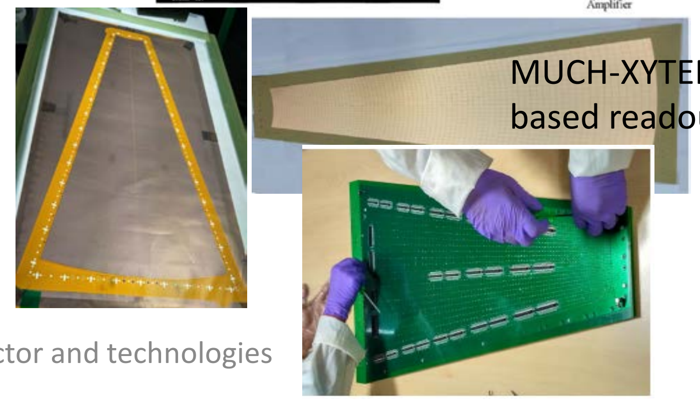
GEM detector technology

$Ar+CO_2$ 70:30



Trigger RPCs
MUCH 3 and 4

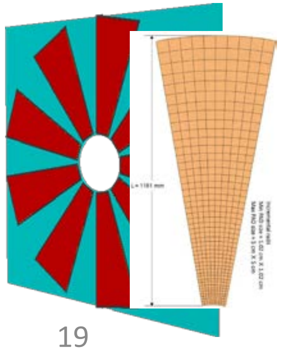




- robust
- low-cost
- fast

~ 1 ns single-gap

~50 ps for multi-gap



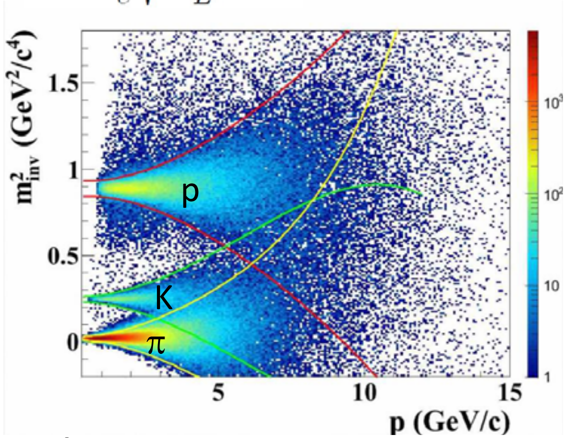
Silicon Tracking System (STS)	track, vertex and momentum reconstruction
Muon Absorber and Chamber System (MUCH)	muon identification
Transition Radiation Detector (TRD)	global tracking
Time of Flight Detector (TOF)	particle identification via time measurement

Time-of-Flight

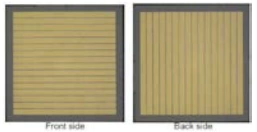
charged hadron identification through Time-of-Flight measurement

$t_{ToF} = t_{sp} - t_{st} - offset(s)$

$$m_0 = \frac{p}{c}\sqrt{\frac{c^2 t_{ToF}^2}{L^2} - 1}$$ (CBM: L = 6 m)

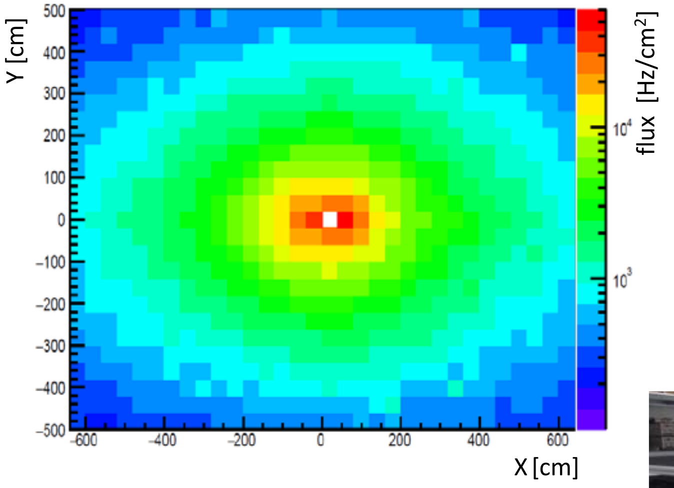


T0 (t_{start}) concepts

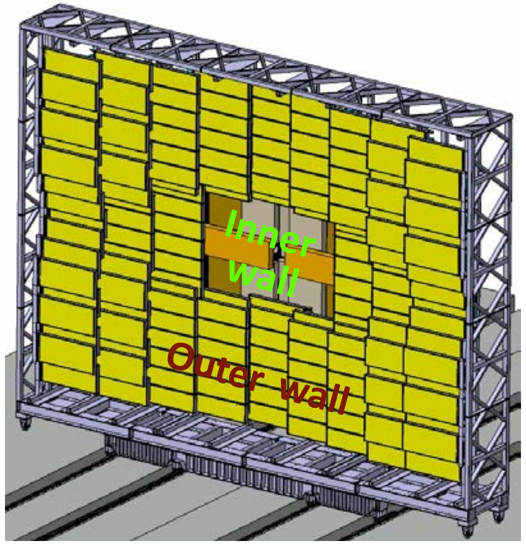


- in beam:
  - diamond counter
    σ ≈ 30 – 40 ps , 100 kHz rate limit
  - LGADs alternative for light systems
- software solution
  - fast particles
    in (semi) central collisions
- fragment counter
  surrounding beam pipe

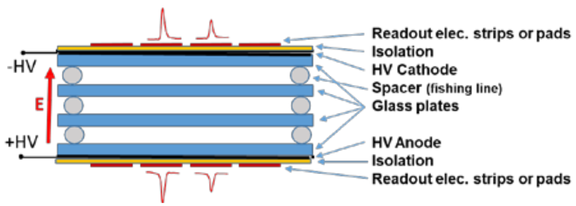
Charged particle flux at L = 8 m from target
FLUKA Au+Au at E_{kin} = 11A GeV, 10^7/s



Detectors with different rate capabilities and granularities needed as function of polar angle.



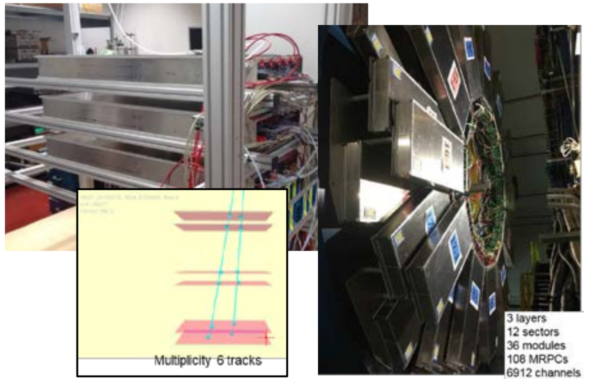
Multi-gap Resistive Plate Chambers



$\sigma_T^{RPC} \approx 40ps$

various variants for CBM:

gaps, glass type + thickness, strip lengths + pitch, outer dimensions, impedance



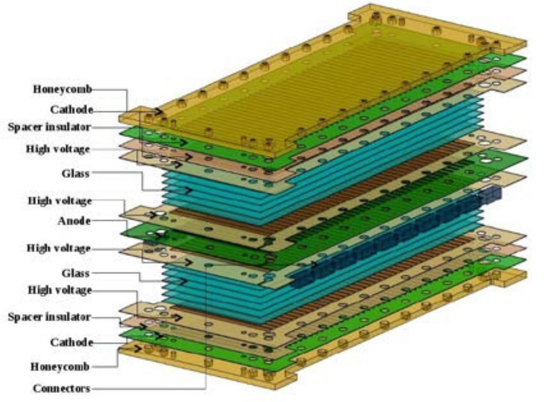
cosmics test stand   eTOF @ STAR

ToF Requirements

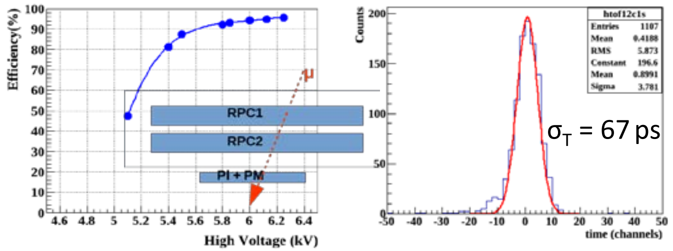
- Full system time resolution σ_T ~ 80 ps
- Efficiency > 95%
- Rate capability ≤ 50 kHz/cm²
- Polar angular range 2.5° – 25°
- Active area of 120 m²
- Occupancy < 5%
- Low power electronics (~120.000 chs)
- Free streaming data acquisition

Inner wall: MSMGRPCs

- highest counting rate
- highest granularity
- ~15 m² active area (up to Θ≈ 11°)
- modular architecture
  - 12 modules, 4 types



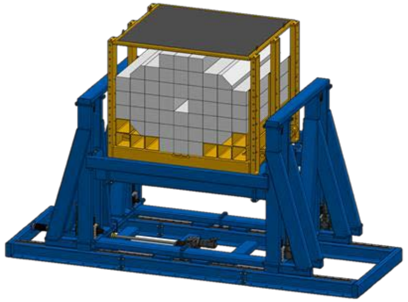
- Symmetric structure: 5 gaps × 2 stacks
- Gas gap thickness: 200 µm
- Active area 60/100/200 mm × 300 mm
- Resistive electrodes:
  ~10^{10} Ωcm, 0.7 mm Chinese glass
- Strip structure for Readout & HV electrodes
- Differential readout



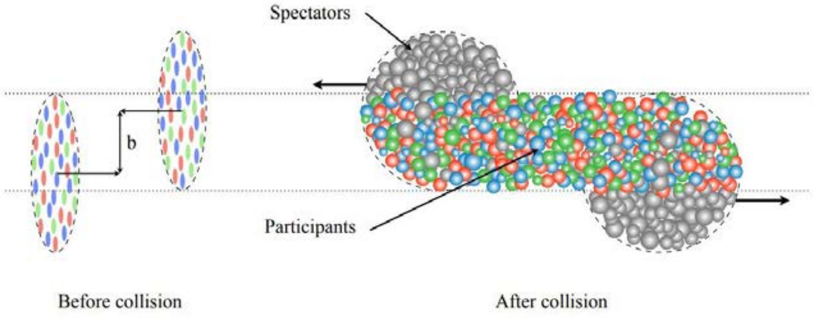
90%$C_2H_2F_4$ + 5%SF_6 + 5%isoC_4H_{10}
NINO FEE (ALICE Coll.) + CAEN TDCs

Projectile Spectator Detector

PSD as proposed in TDR



determination of centrality and even plane of the collisions



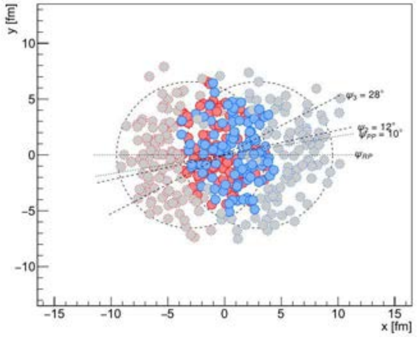
$N_{spec} = A_{proj} + A_{targ} - N_{part}$

N produced particles ~ N_{part} "wounded nucleon"

Many physics variables are highly dependent on the centrality: kinetic freeze-out temperature, multiplicity of produced particles, flow...

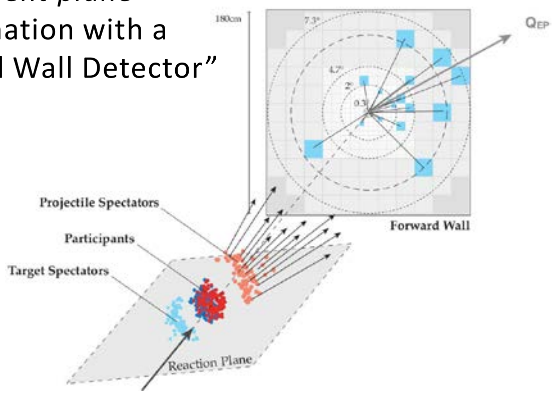
Wanted: *"reaction plane"*

- defined by vectors of beam direction and impact parameter
- no direct measurement possible.



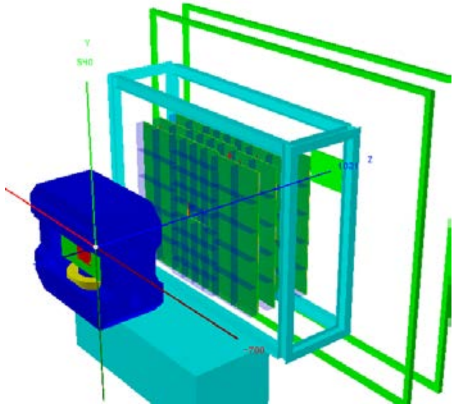
Instead: *"event plane"*

- determination with a "Forward Wall Detector"



- compensating sampling calorimeter
- sandwich Pb/Scint ratio 4:1
- 44 modules, aperture 0.21° < Θ < 5.7°
- 6.5 l, good energy resolution ~55%/√E
- light readout from a section through
- WLS fibers by photodiodes
- 20 × 20cm beam hole in the center, reducing radiation damage
- total 22 tons of weight on a platform movable in 3 dimensions

CBM hadron setup with PSD replaced by a FWALL? scintillators BC408 + SIPMs

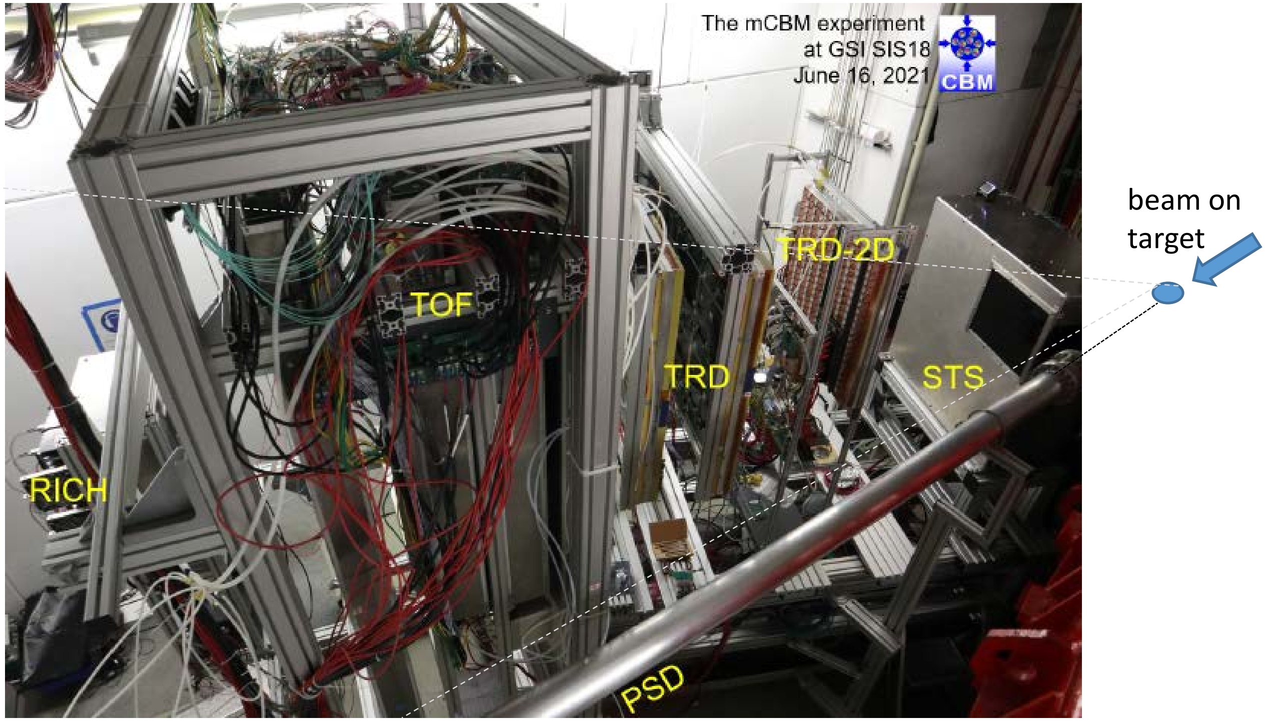


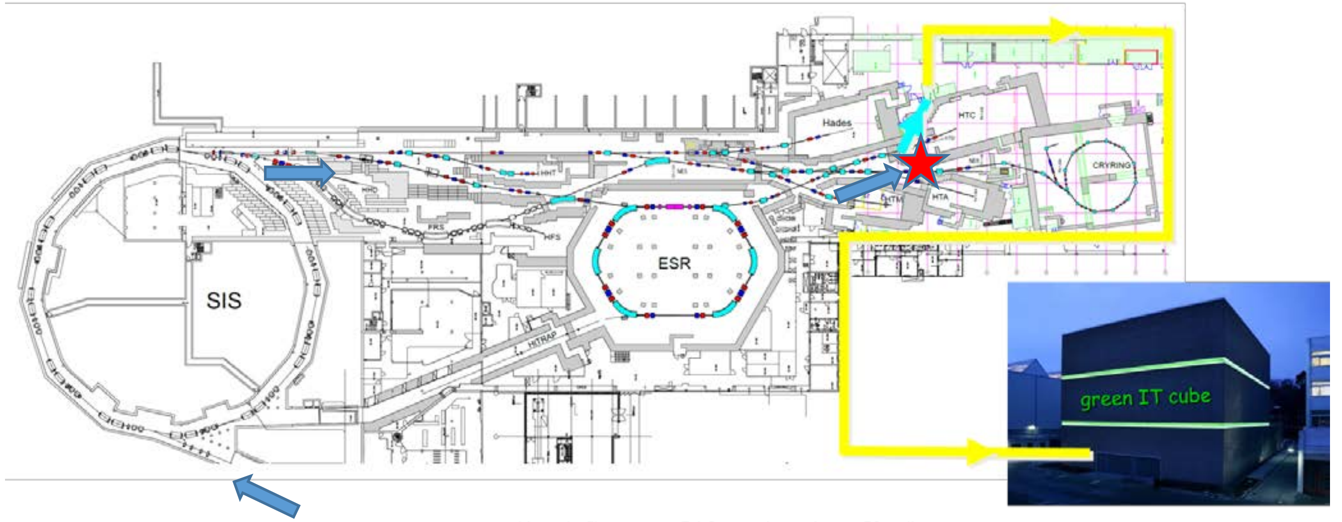
mCBM @ SIS18

CBM full-system test-setup,
a slice in Φ of CBM detector systems, Θ = 2.5° – 25°

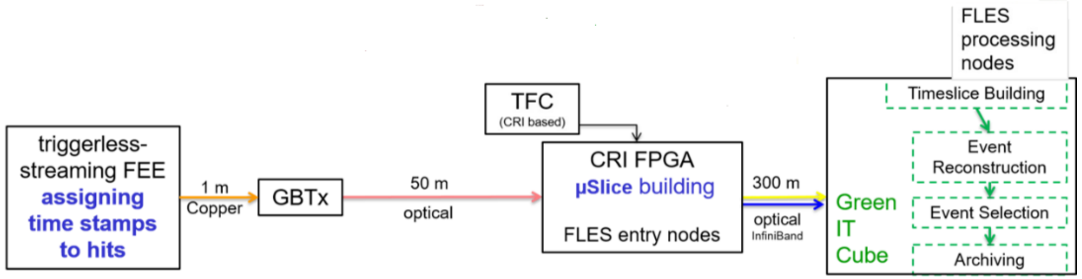
set up from 2017/18 at HTD detector test area of SIS18

- *commission and optimize the complex interplay of the different detector systems with the trigger-less streaming data acquisition and the fast online event reconstruction and selection.*
- *test detector and electronics components developed for CBM, as well as the corresponding online/offline software*
- *under realistic experiment conditions up to the top CBM interaction rates of 10 MHz.*





multi-mode fiber cave – DAQ container, about 50m distance
single-mode fiber DAQ container - GC, about 300m distance

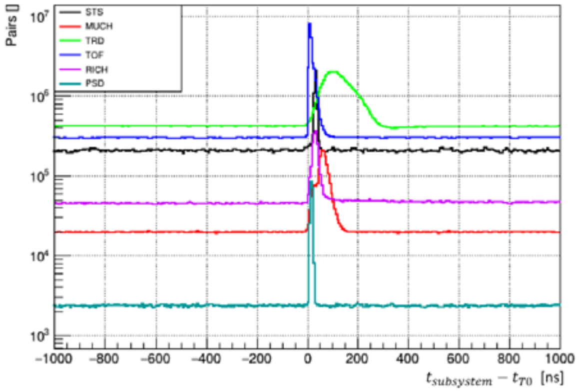


mCBM @ SIS18

a look at few of the many results

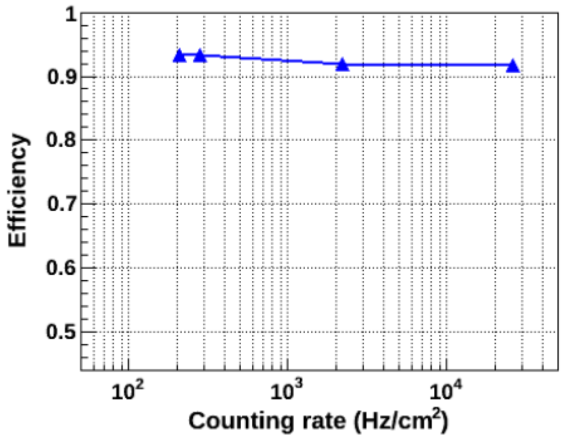
time correlation and stability of subsystems (2020)

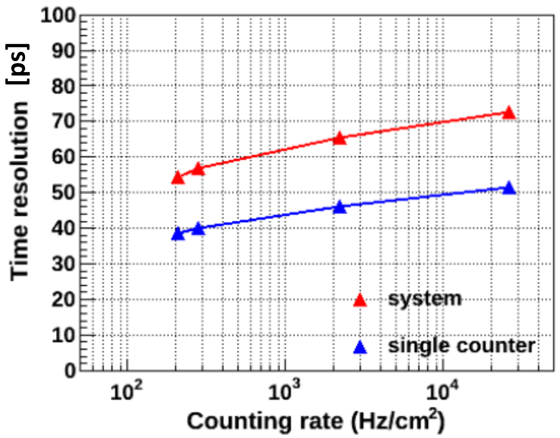
- *^{208}Pb+Au at 1MHz*
- *offsets corrected*



high-rate tests with TOF – RPCs (2021)

- *2 AGeV ^{16}O beam, 10 s spills*
- *4 mm Ni target*
- *10^8 – 10^{10} beam particles/s*





mSTS demonstrator (2021)

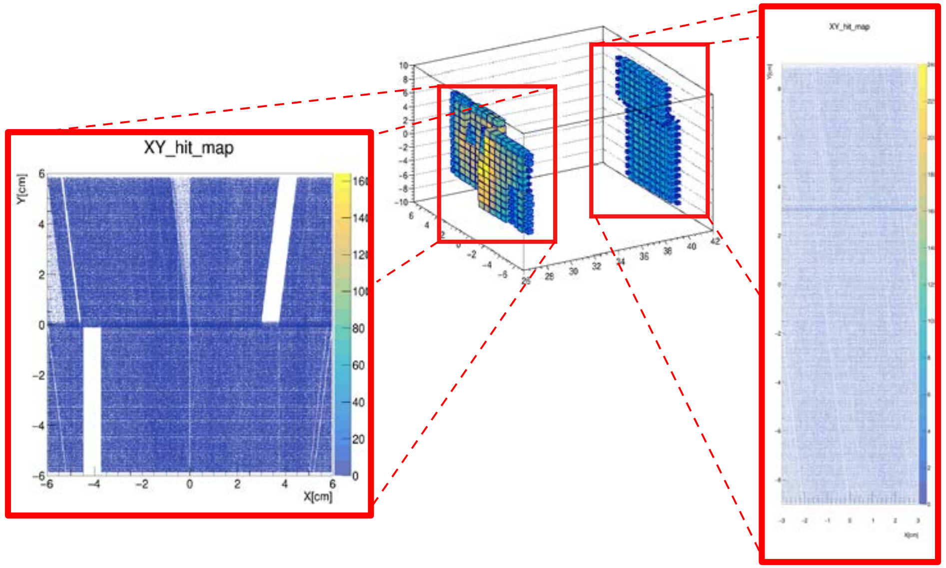
O+Ni at 2 AGeV, 10^{10} ions per spill, ~ 500 kHz int. rate

- *2 tracking stations*
- *4 mechanical units*
- *11 modules*
  (various prototype component versions, 2017 – 2021)
- *mounted on 5 detector ladders*
  with carbon-fiber support frames

mSTS performance (2021)

Operational!

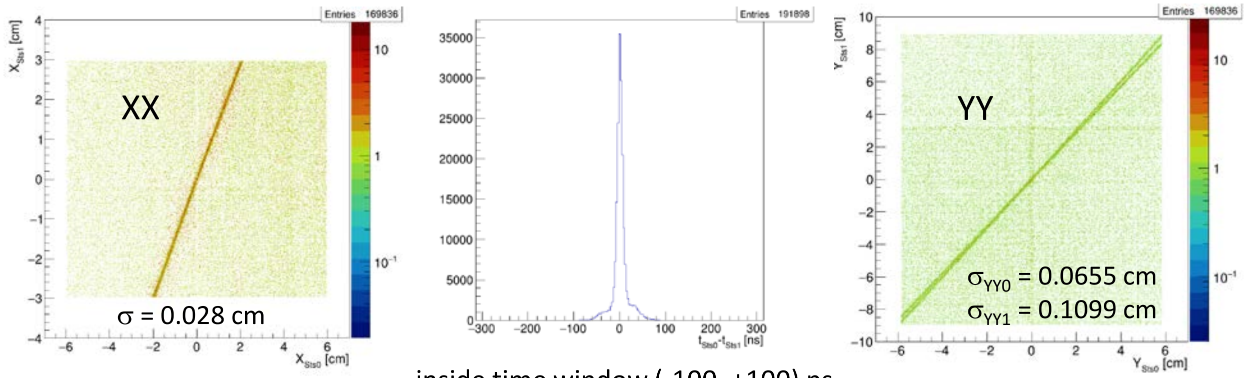
- *Just few r/o ASICs not read-out, few individual channels missing/masked*
- *3D hits maps, projections onto tracking layers*



- *Charge calibration: MIPs clearly in range*

- first performance results match expectation
- much more to come … analysis of mCBM campaign 2022

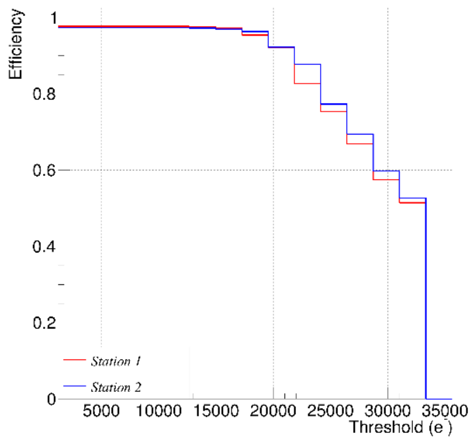
- *Correlations of hit pairs STS1:STS2 (hit time resolution 5 ns)*



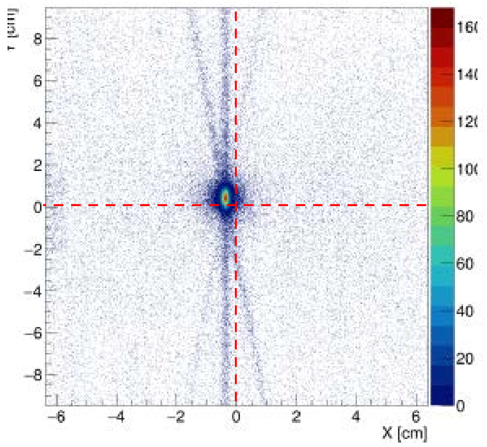
inside time window (-100, +100) ns

fits with simulation

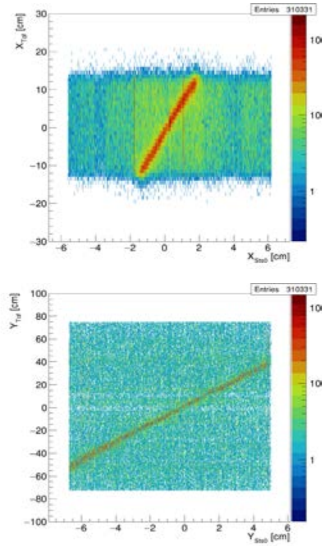
- *Fraction of correlated hits as function of r/o threshold*



- *Target extrapolation STS1:STS2 with simplified alignment*



- *Correlation mSTS0:TOF*



Summary

- CBM requires detectors, as well as data transport, processing and analysis, capable of registering the imprints of high-rate nuclear collisions beyond example in heavy-ion physics.
- Suitable state-of-the art techniques have been chosen in CBM-specific adaptations.
- Prototypes detectors have been developed, performance tests made, showing the CBM requirements reached / in reach soon.
- Construction of many systems is to start shortly, the site infrastructure is far advanced.
- For deeper insight, refer to e.g. the Technical Design Reports as pointed to in the References.
- Due to sanctions in response to Russia's war on Ukraine, several components from Russia have become unavailable to the CBM project, entire teams are suspended from the Collaboration. E.g. the superconducting dipole magnet - efforts on replacement are being made.

Acknowledgements

- Much input and material used from my CBM colleagues, without explicit mentioning.
- It's a great pleasure, and trust in CBM, that STS modules from the pre-series production, and read-out components, will be used in the ongoing upgrade of J-PARC E16.

CBM-STSモジュールを楽しみにしています 2023年春のJ-PARC E16実験で

References

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  N. Herrmann, Proc. SQM 2021
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- CBM Technical Design Reports: https://www.cbm.gsi.de/documents