Modern 3D-Detectors

Instrumentation for Particle Tracking in Nuclear Collisions

Outline

- “historic” 3D detectors
  - ➢ limited in speed, mostly visual

- modern 3D detectors
  - o two examples:
    - o ALICE Time Projection Chamber after GEM upgrade
    - o CBM Silicon Tracking System
  - ➢ modern detectors require fast, sophisticated online reconstruction software,
  - ➢ detection system = detector + high performance computing

Very First 3D Detector

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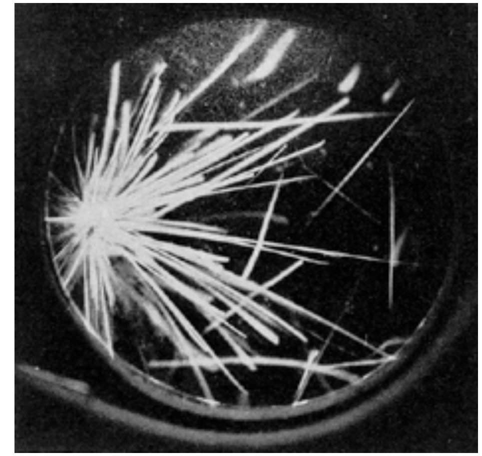
original Wilson Cloud Chamber (museum Cavendish laboratory) – Nobel prize 1927



tracks of an α–source in a cloud chamber

spatial resolution:
< 1 mm

sensitive time (by adiabatic expansion) : 0.01 sec
recovery time: 1-2 min (or longer)

integration time: $> 10^4$ µs
rate: $< 10^{-2}$ Hz

Best Spatial Resolution Ever to-Date…

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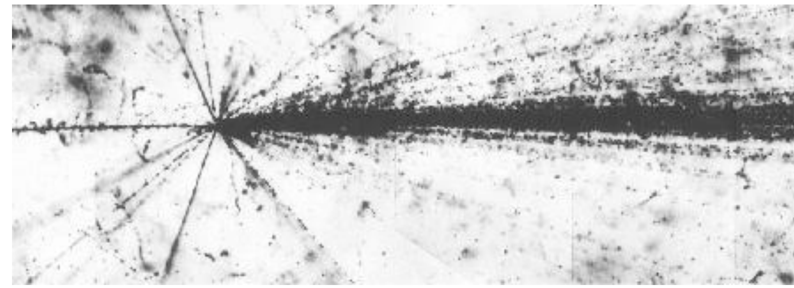
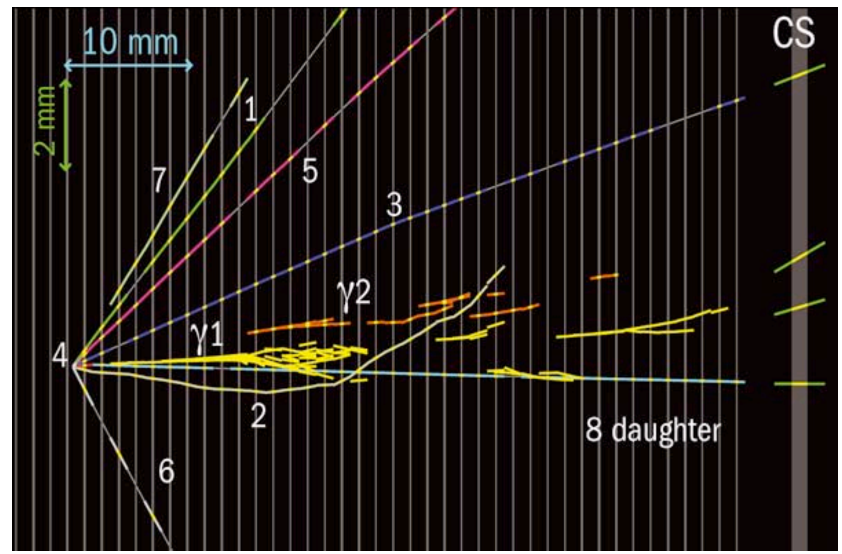
Emulsion Chambers

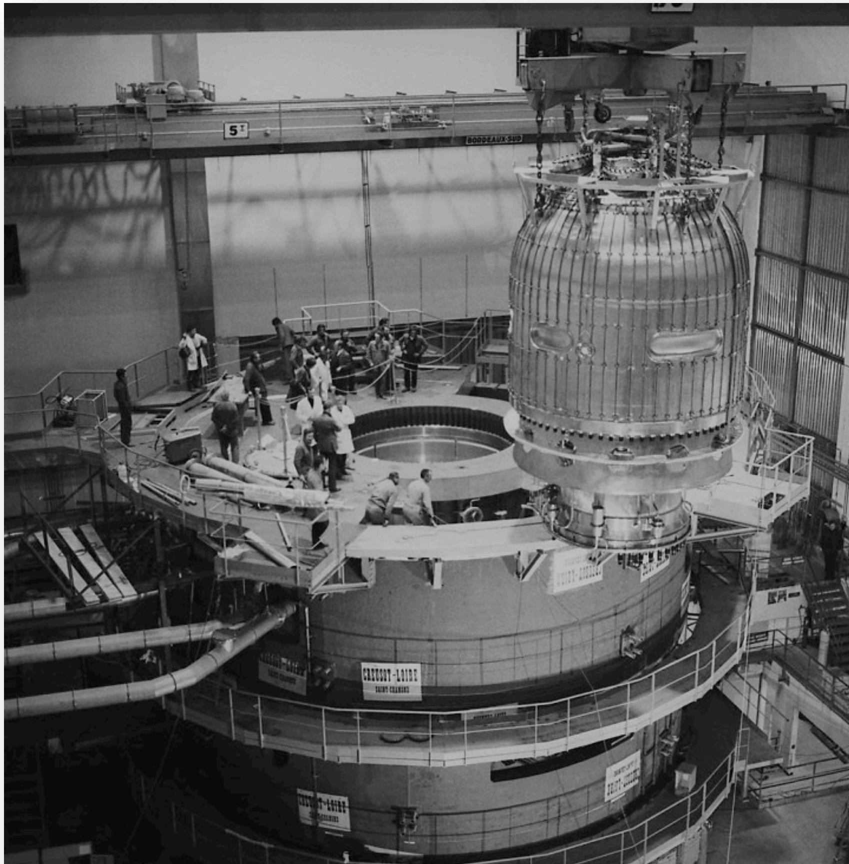
spatial resolution given by grain size – 0.2 µm

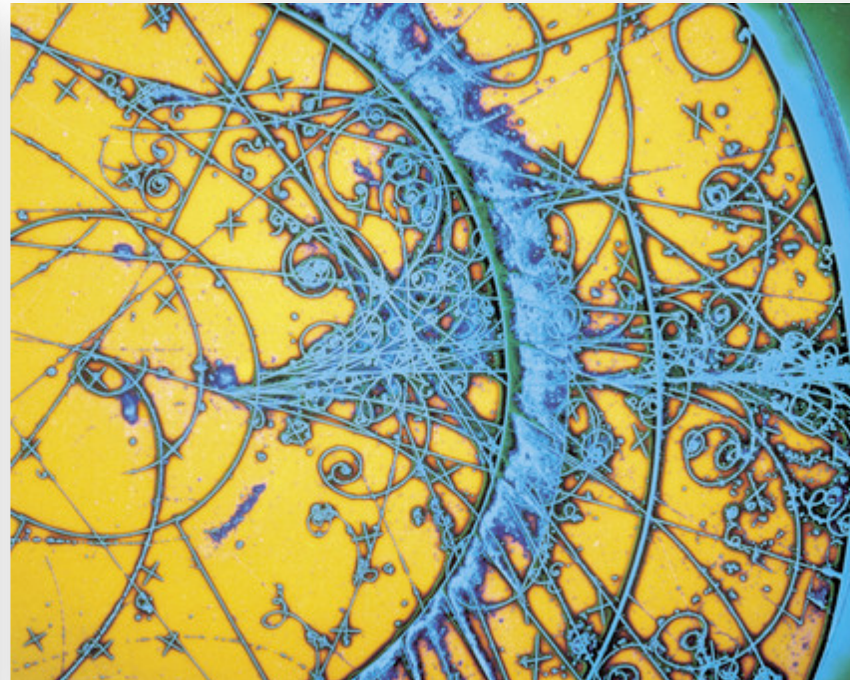


used from 1940 until today (e.g. **O**scillation **P**roject with **E**mulsion-tRacking **A**pparatus - OPERA)



one of the last of its kind…

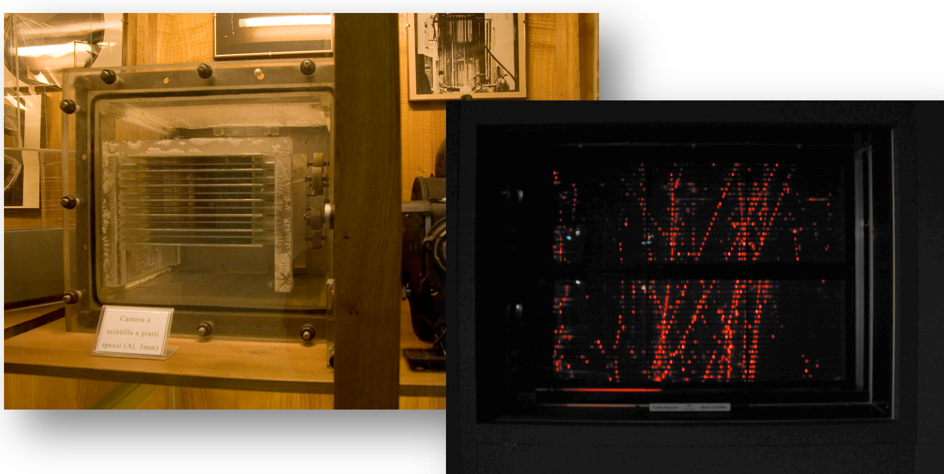


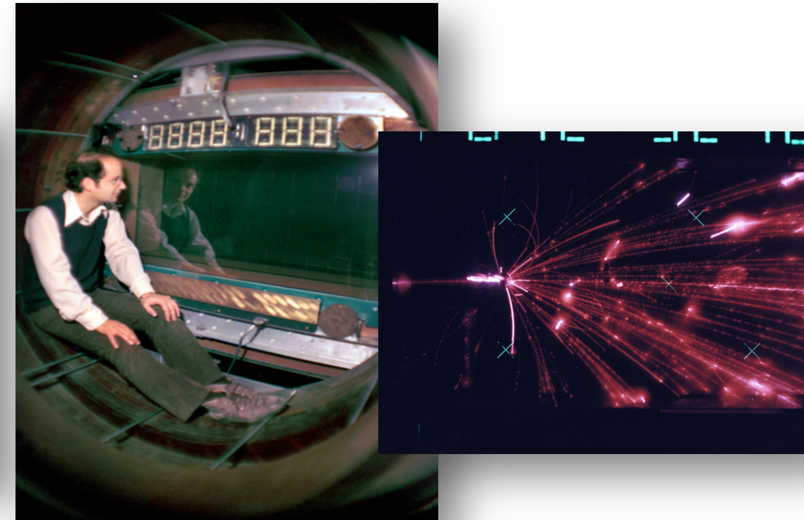


spatial resolution: < 100 µm

BEBC - Big European Bubble chamber, in operation 1977 – 1984 at CERN
during this time 6.3 M photos were taken (data taking rate ~10^{-2} Hz)

More visual 3D Detectors…





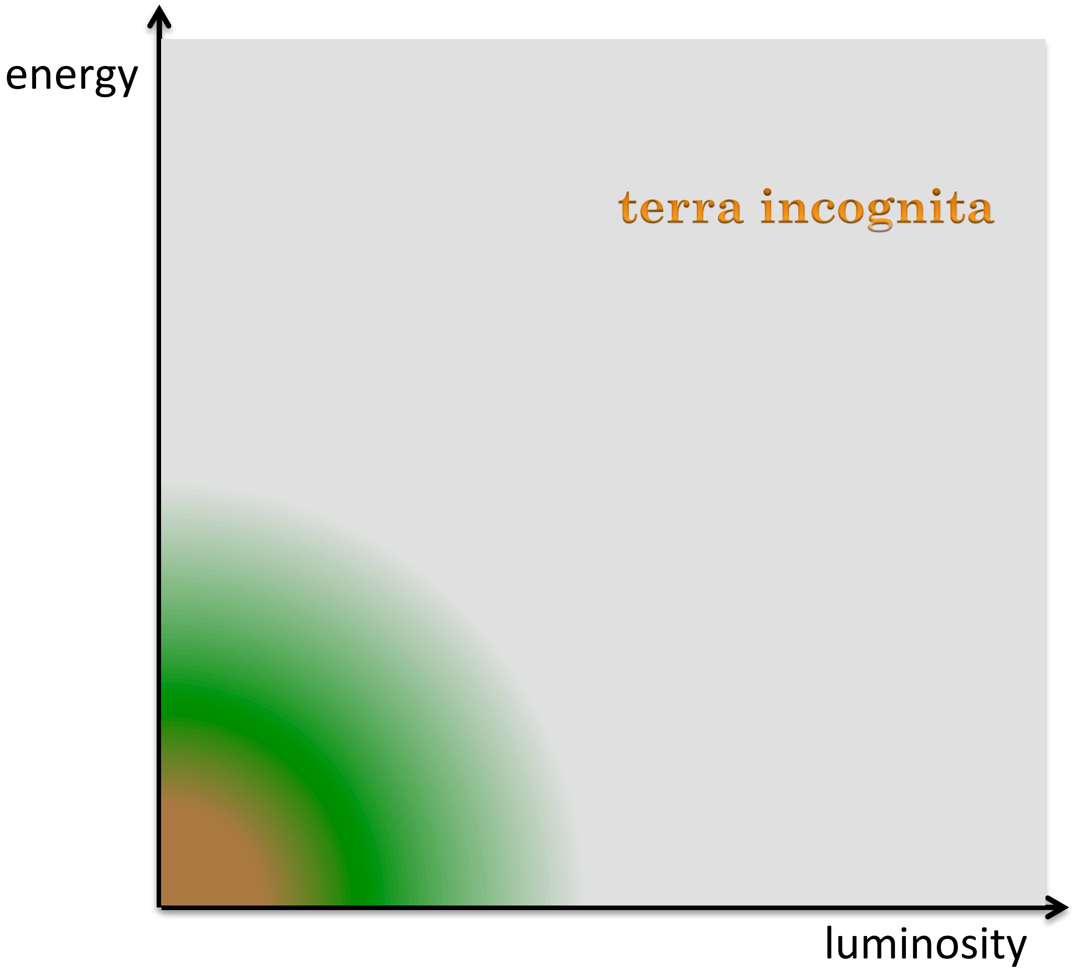
spark chamber
dead time ~ up to *ms* (clearing field for ions)

streamer chamber

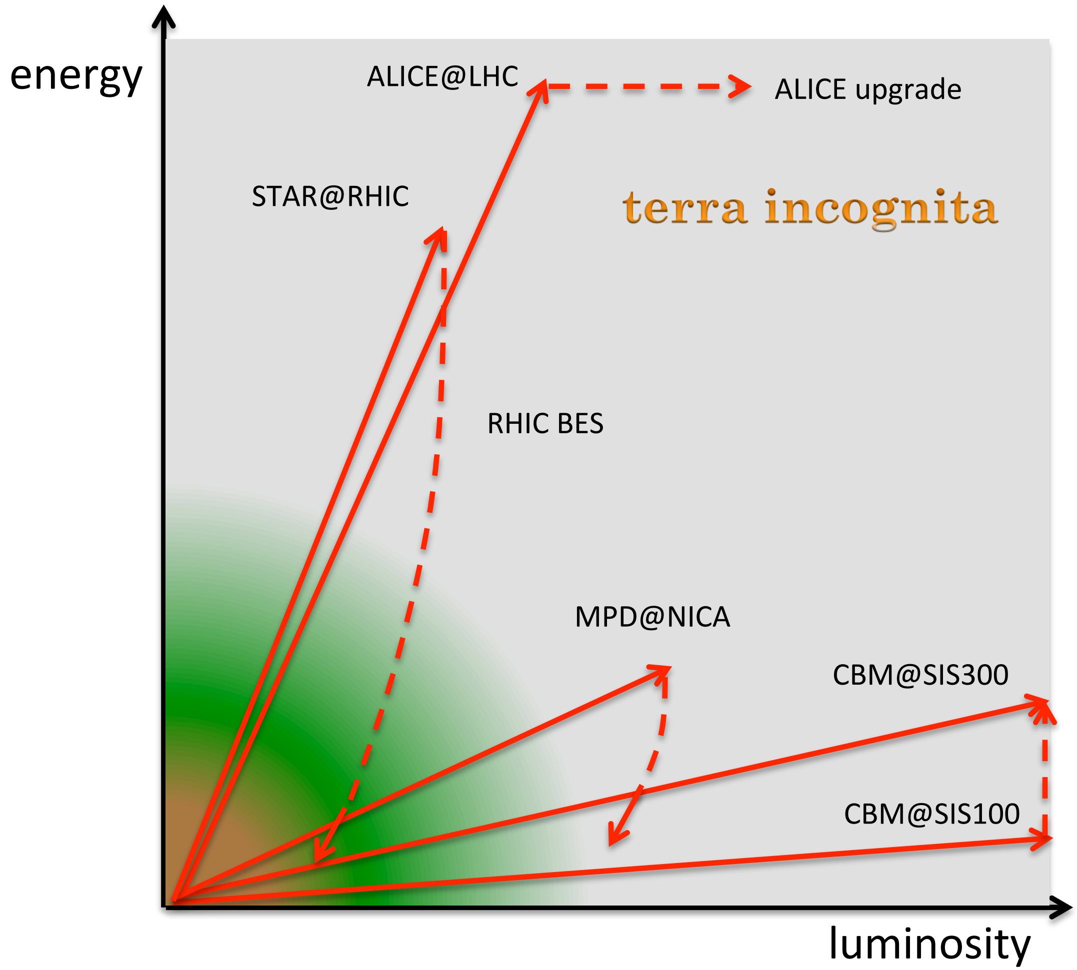
rate limited by optical readout

breakthrough: invention of wire chambers/drift chambers
→ electronic recording of 3d space points in kHz range…

Landscape of Discovery in Super-Dense Matter Physics



Landscape of Discovery in Super-Dense Matter Physics



Modern 3D Detectors

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requirements for the exploration of the terra incognita:

- high multiplicity
- rate capability & radiation hardness
- low mass budget

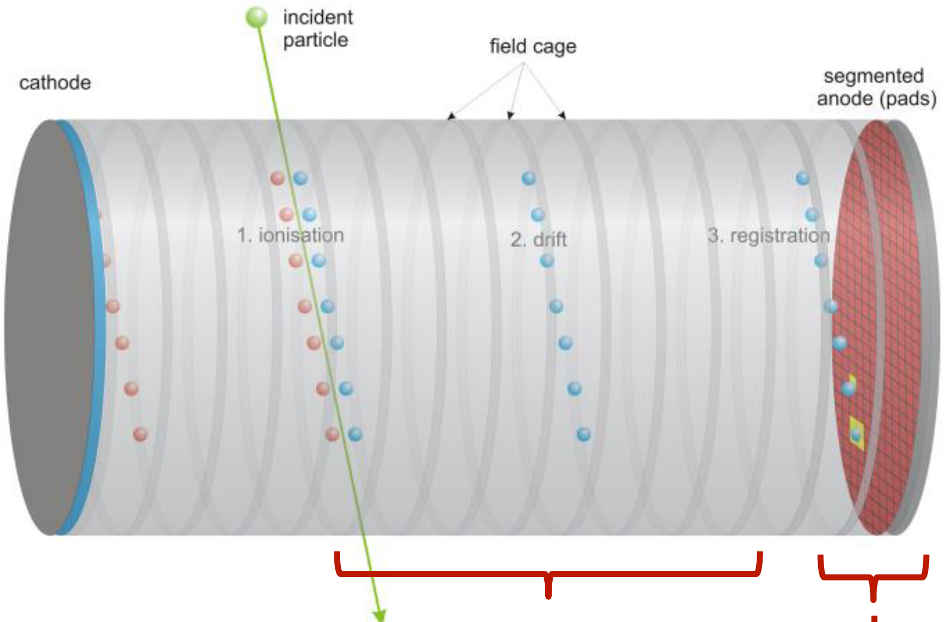
in addition to:

- very good momentum resolution
- very good position/impact parameter resolution
- two-track resolution
- particle id
- …

- no detector can fulfill all requirements simultaneously,
- in this talk the state-of-the-art will be discussed on the basis of the
- ALICE TPC-upgrade plans
- future CBM silicon tracking system (STS)

modern 3D detector require very careful optimization of its operation conditions

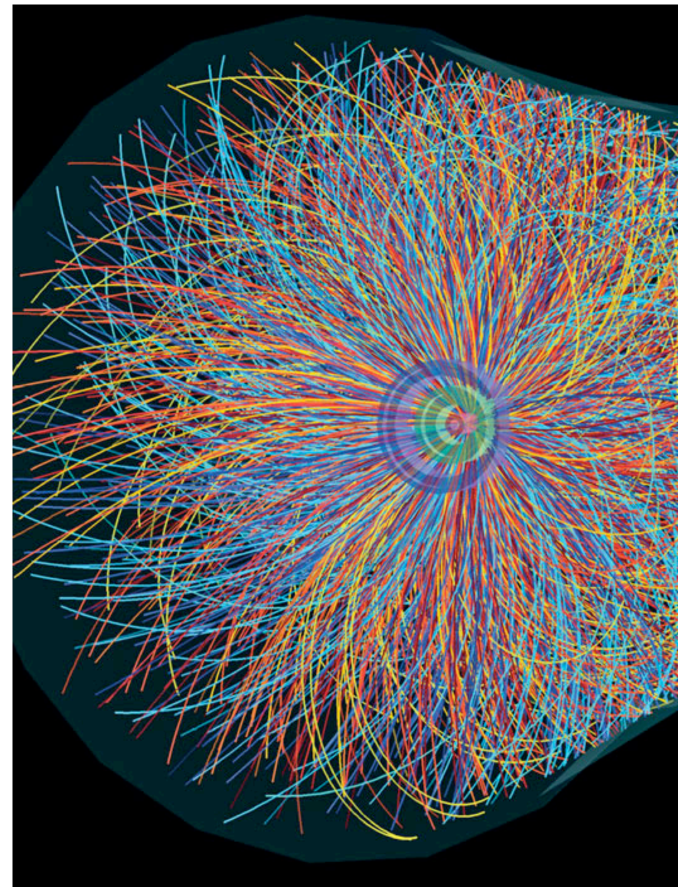
TPC - Principle



1D z-drift-direction

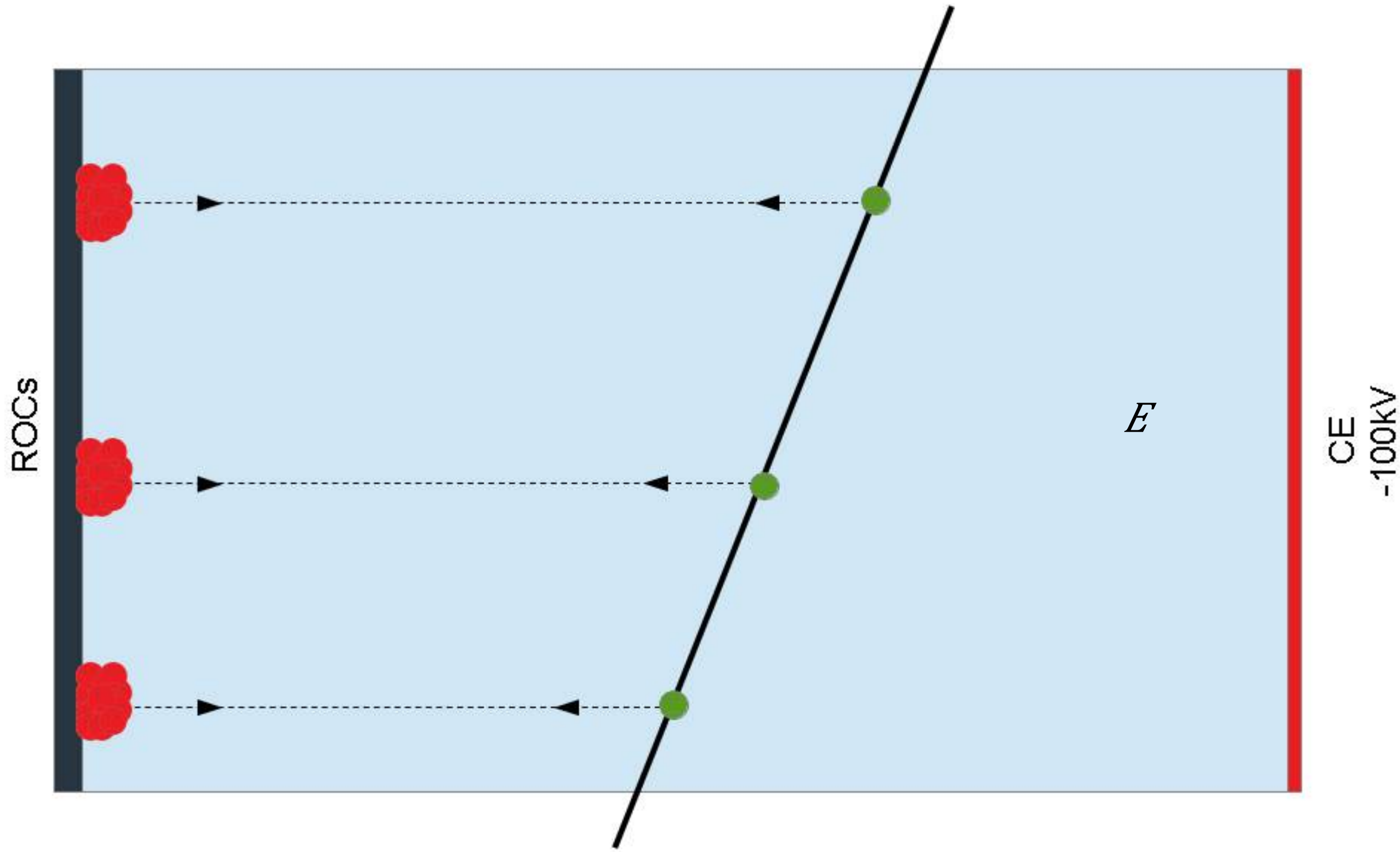
2D x-y-readout
plane

allows continuous 3D-tracking of high
multiplicity events and PID



ALICE PbPb event

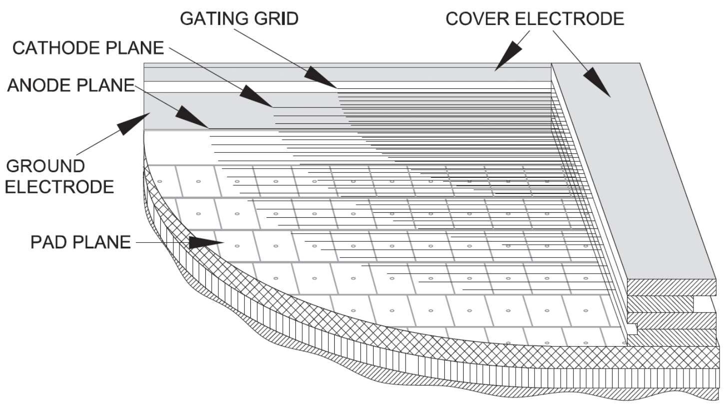
The Space Charge Problem



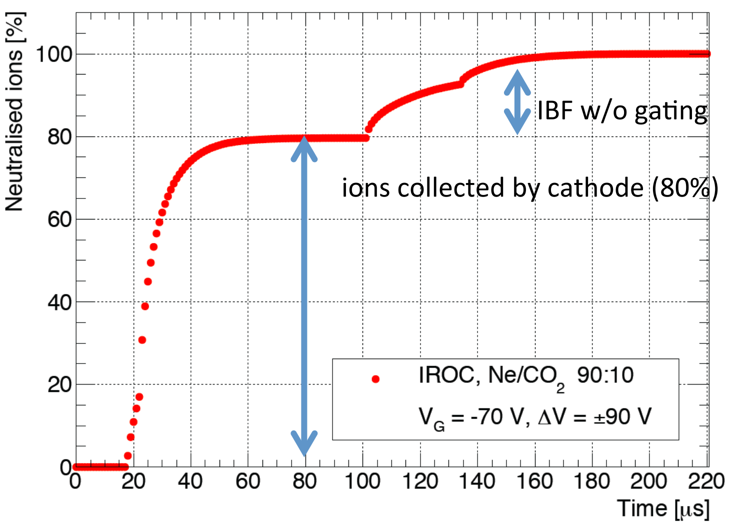
- due to their slower drift velocity positve ions accumulate in the drift space end eventually distort the drift field
- at 50 kHz interaction rate ions from 8000 events fill the drift space!

TPC-Limitations: Space Charge

"conventional" MWPC readout



time needed to "neutralize" ions



- present TPC employ MWPC with gain up to 10^4, i.e. ion back flow (IBF) of $2x10^3$ ions/electron
- gating grid needed to suppress IBF
  - after electron drift (100 μs) the gate must be close for 200 μs to suppress back-drifting ions
  - total time of 300 μs limits the maximal trigger rate to 3 kHz (if one wants to avoid excessive space charge accumulation)

▶ in this configuration a TPC cannot be used for high luminosity experiments (e.g. after the ALICE upgrade or at the ILC/CLIC)

Readout Planes w/o IBF

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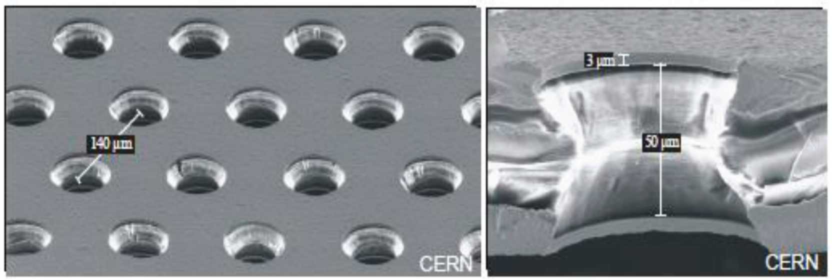
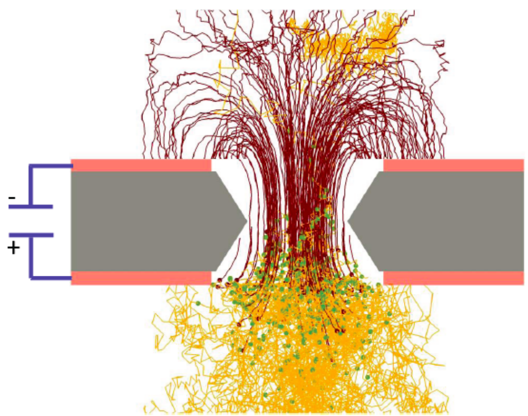
Gas Electron Multiplier

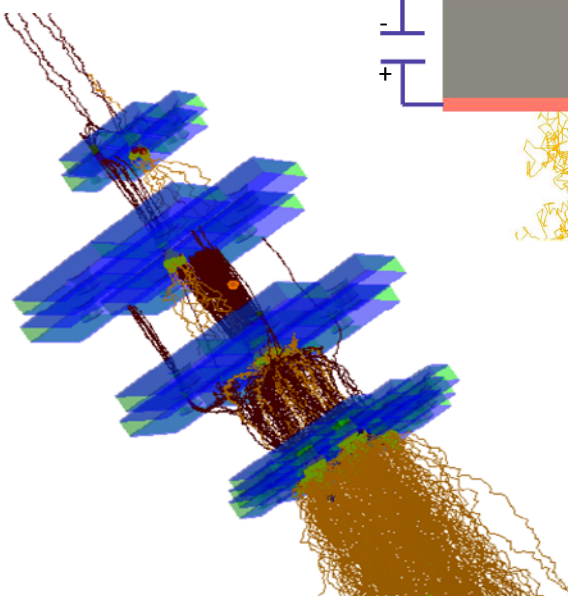


Electron microscope photograph of a GEM foil

promising candidates for amplification stages with reduced IBF are MPGC (Micro Pattern Gas Chambers) like

- GEM (Gas Electron Multiplier)
- MicroMegas



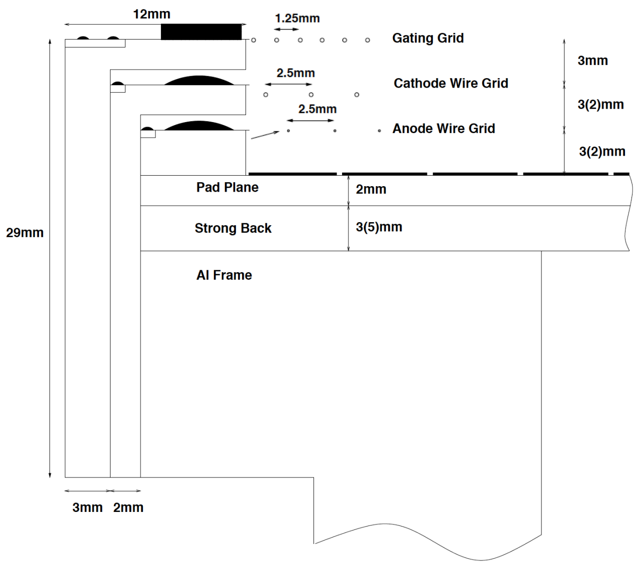


goal for IBF: < 1 % (<20 ions flow back into drift space at a gain of 2000)

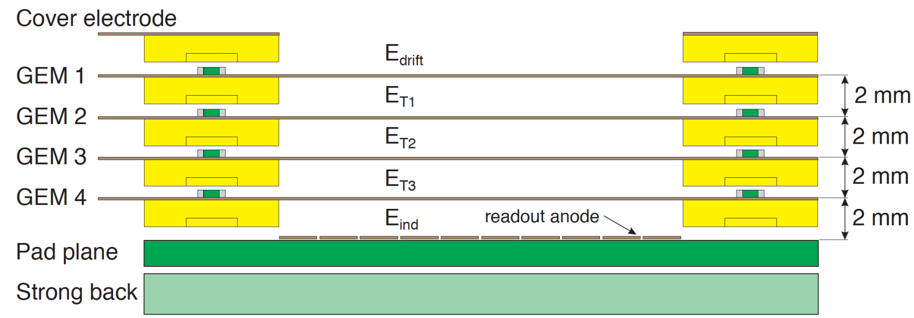
reduction of IBF is achieved by a stack of 4 GEM planes and optimized transfer fields between GEMS

4-GEM Stack

MWPC

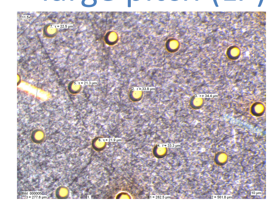


GEM



small pitch (S)

large pitch (LP)



conventional MWPC replaced by stack 4 GEM foils

overall IBF depends on many factors (large parameter space):

- $E_{T1,2,3}$ (transfer fields), E_{ind} (induction fields)
- $E_{GEM1,2,3,4}$
- hole geometry & alignment, …

requires significant R&D

goal for IBF: < 1 % (<20 ions flow back into drift space at a gain of 2000, ε < 20)

IBF vs. Energy Resolution

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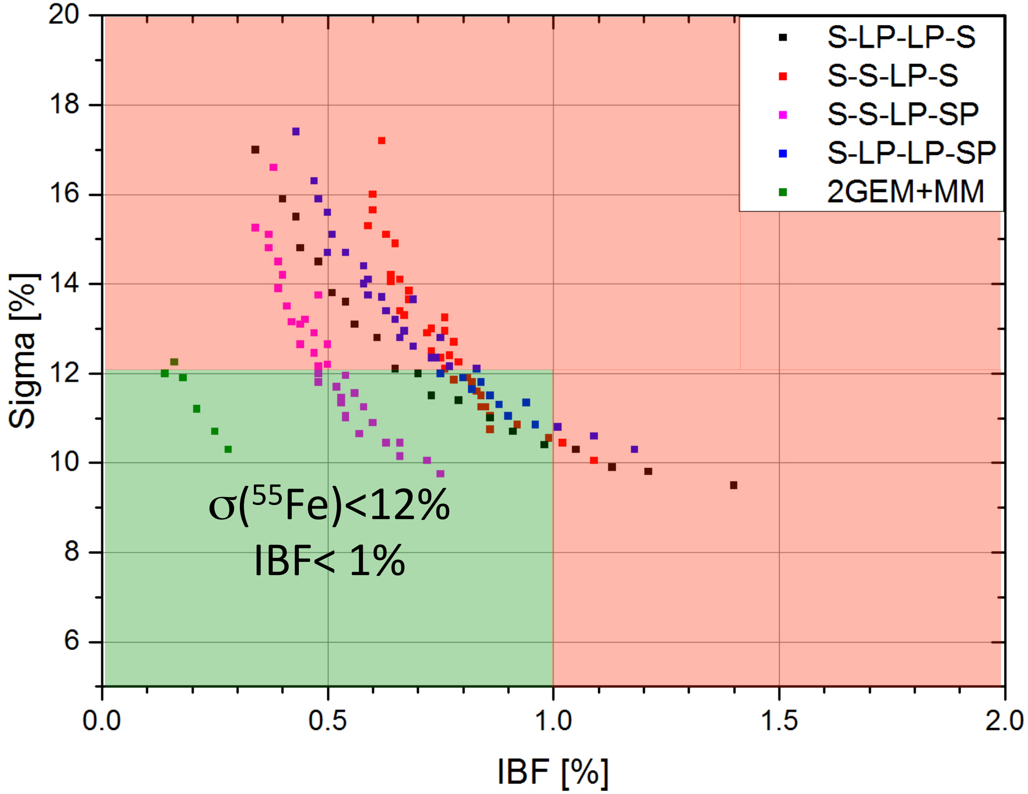
Basic caveat:

minimization of IBF reduces at the same time the transparency for electrons, i.e, the energy resolution….



Technical Design Report: base line solution with 4 GEM-system with IBF <1% and $\sigma(^{55}Fe)<12\%$

Space Charge Distortions with IBF=1%

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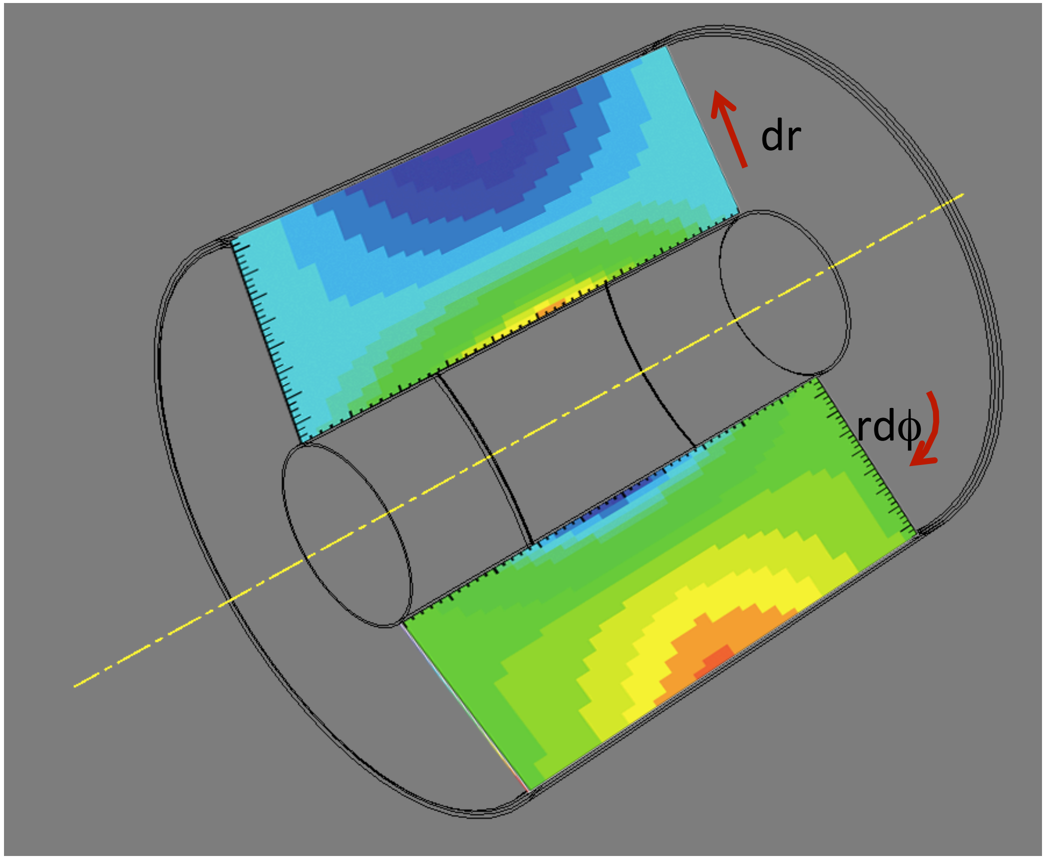
space charge distortion based on average space charge density at 50 kHz interaction rate, corresponding to a pile-up of positive ions from 8000 events



distortions in radial direction:
dr < 19 cm

distortions in azimuthal direction:
rdϕ < 4 cm

required precision: ~ few 100 μm

can this be corrected? → yes, but….

- correction must be done on the fly
- space charge distribution fluctuates (multiplicity, event rate, ionization) ~ 5%

Data Size & Online Reconstruction

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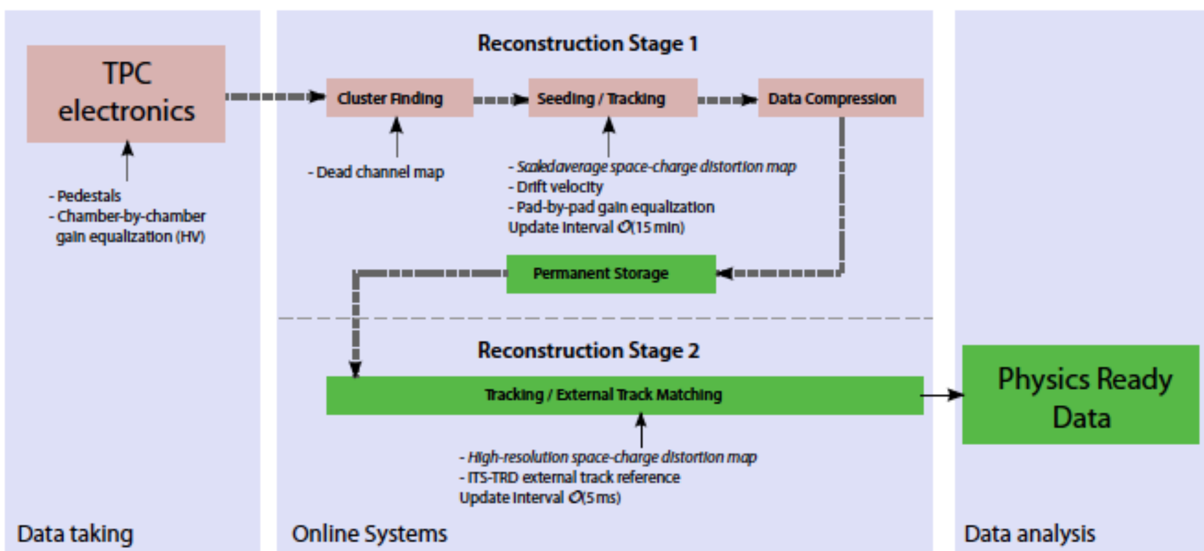
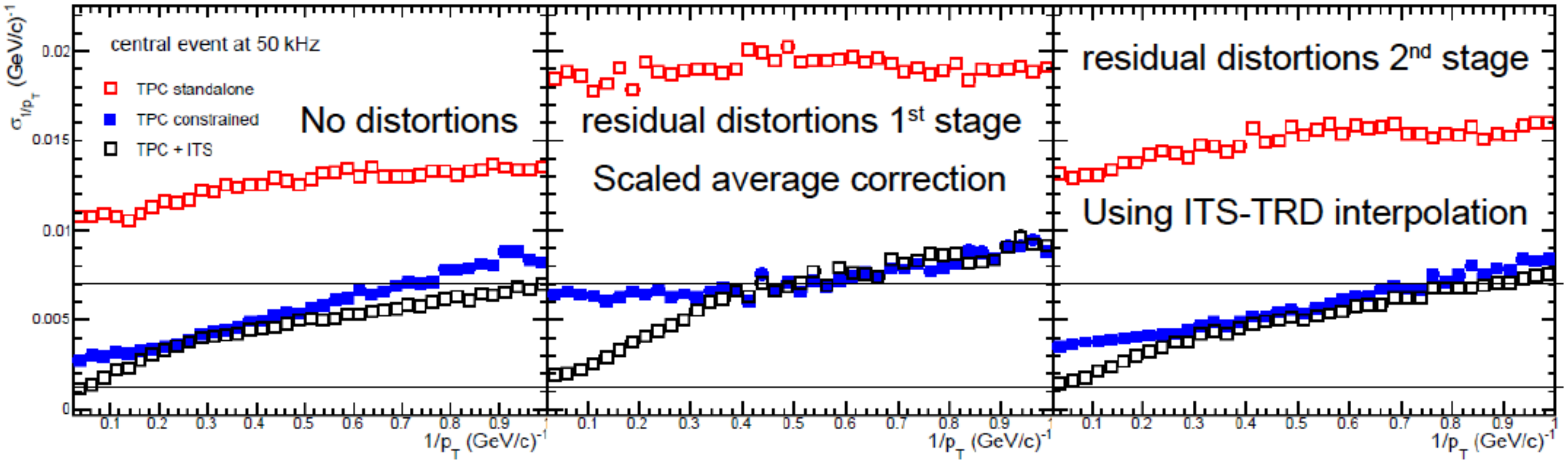
typical TPC raw events size: 20 Mbyte
data rate @ 50 kHz: 1 TByte/s

exceeds storage band width by far
⇒ online data correction & compression

- the required compression (> factor 20) can only be achieved if tracks are online reconstructed based on an average distortion map, which must be updated every 15 min
  → permanent storage
- the final correction is based on a high resolution distortion map, which must be updated every 5 ms
  → requires external track reference from other detectors (ITS, TRD)



Performance: Momentum Resolution after Corrections



TPC momentum resolution for tracks matched with the ITS/TRD practically restored after 2nd reconstruction stage!

The CBM Silicon Tracking System

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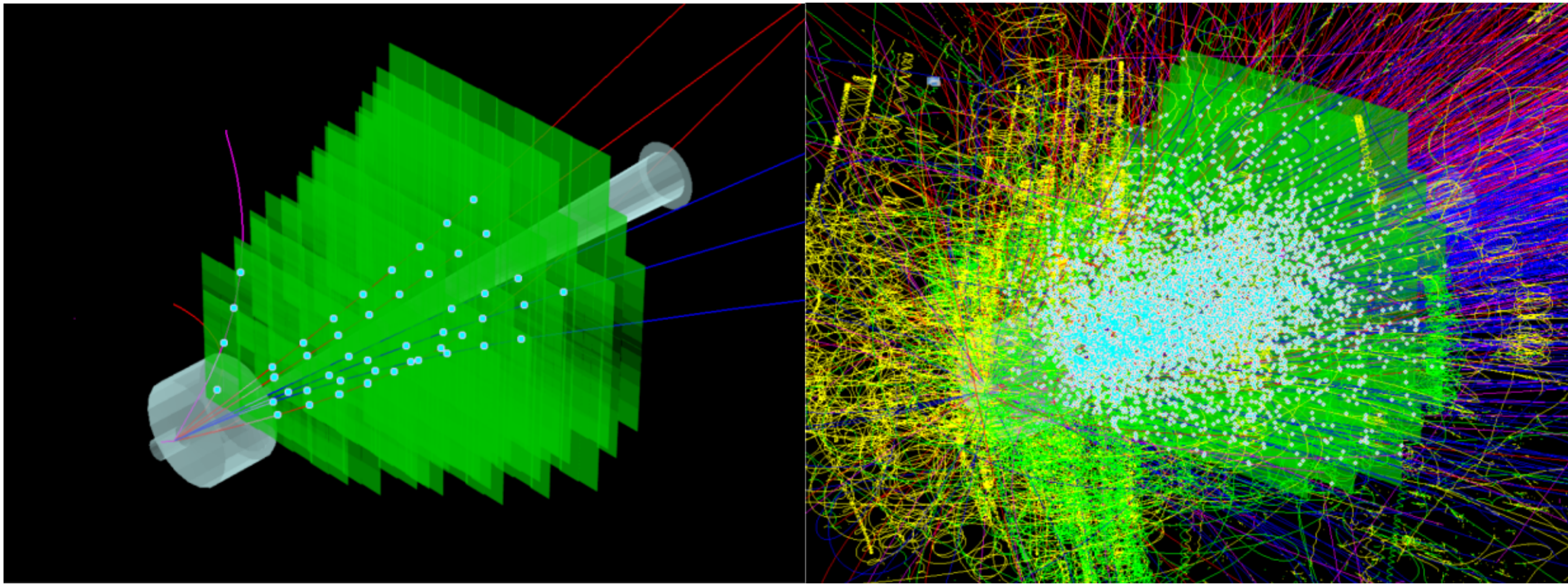
silicon sensors (pixel or strip) are inherently 2D-devices, they become 3D by stacking several sensors:



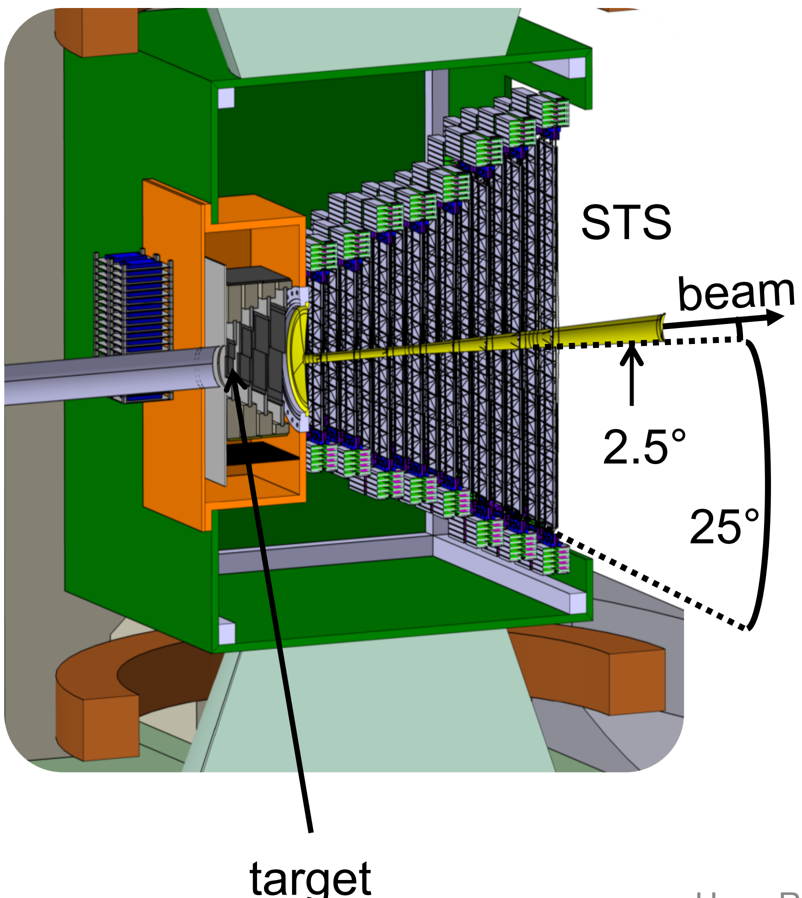
can a 3D-Silicon Tracking System meet the ambitious CBM requirements?

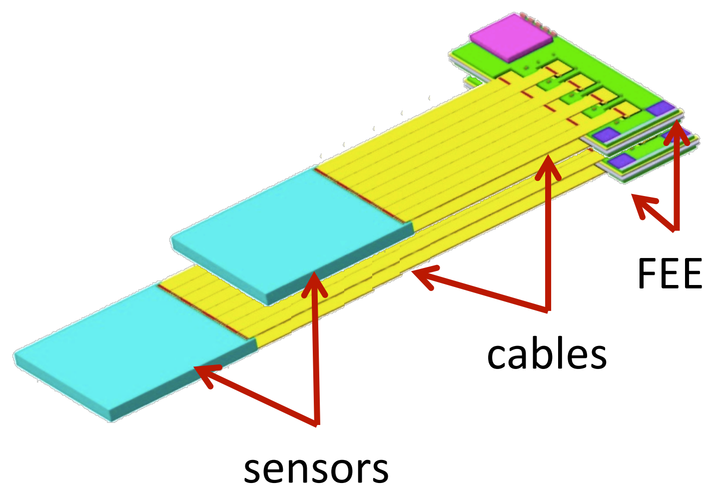
I. excellent momentum resolution ($\Delta p/p \approx 1\%$) at low momenta (<10 GeV/c) ⇔ material budget
II. simultaneous tracking of several hundred particles ⇔ granularity
III. high collisions rate of up to 10 MHz (TPC 50 kHz) ⇔ readout and rad. hardness

I.1: Momentum Resolution & Material Budget

At SIS-energies (and design spatial resolution < 25 μm) the momentum resolution is dominated by multiple scattering, i.e., for good momentum resolution the active area has to be practically massless….

- readout electronics outside of active area
  - ultra-thin readout cables
- ultra light support structure
  - carbon fiber
- 300 μm sensor with double sided readout

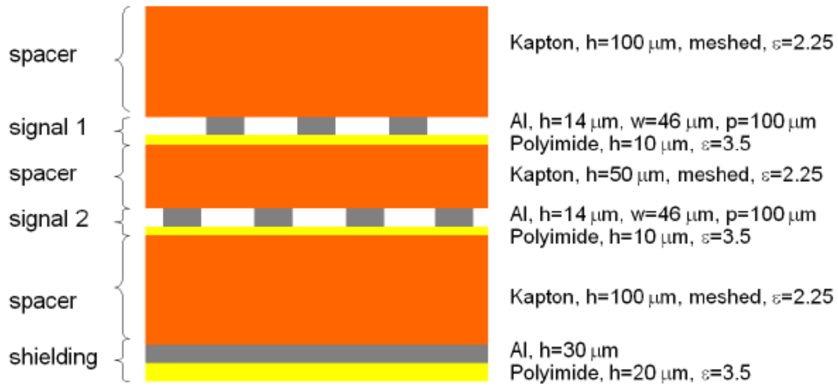




I.2: Multilayer Readout Cables

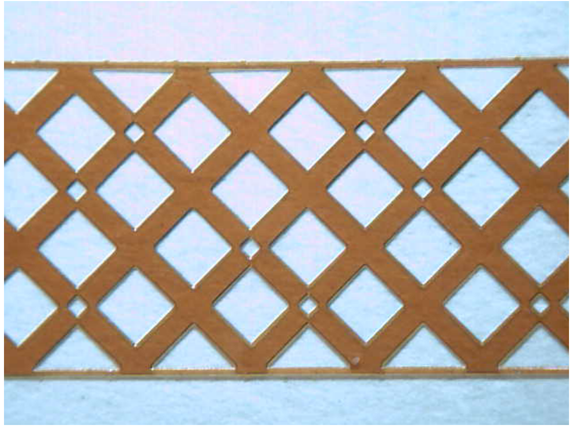
caveat 1: long readout cables to periphery has large capacity (noise)
caveat 2: spacer to decrease capacity of signal lines increases material budget

cable stack: *thickness 0.11% X_0*



signal lines: h=14 µm Al, w=46 µm

meshed spacer layer



cable design is a optimization between capacity (noise) and material budget (multiple scatt.)

I.3: Carbon Fiber Support Structures

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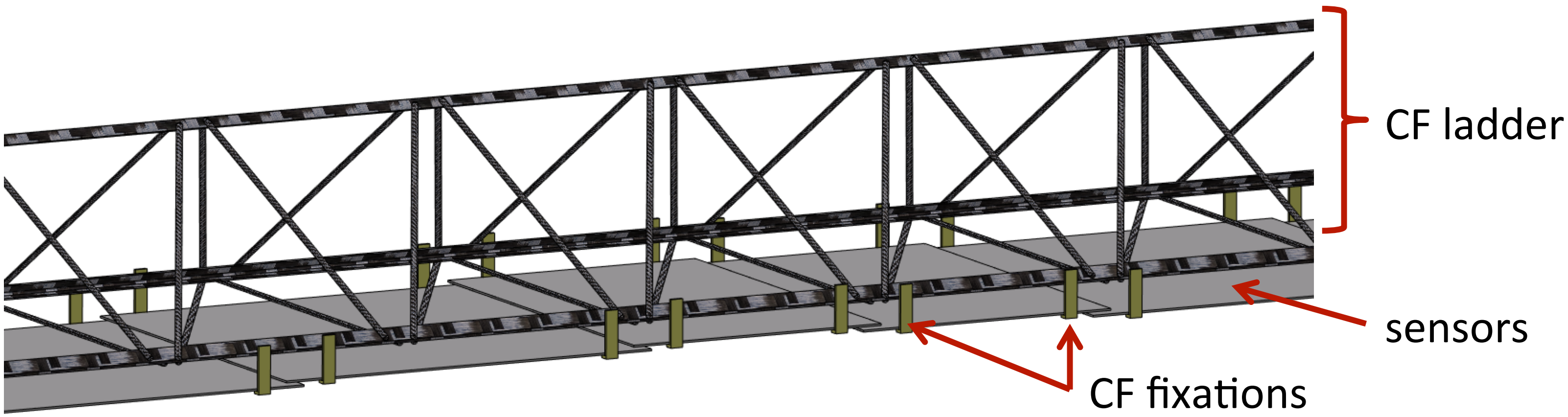
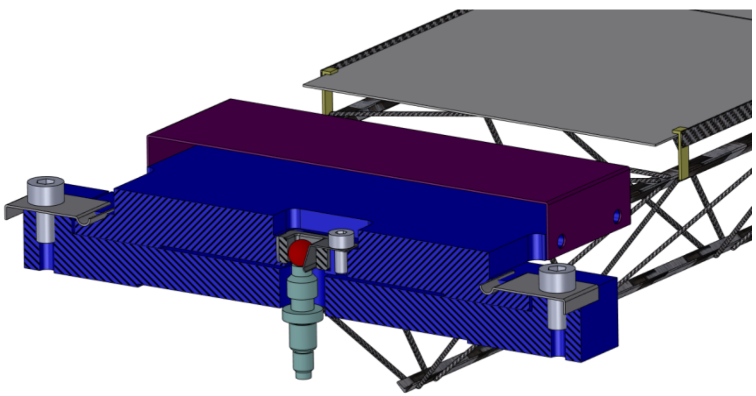
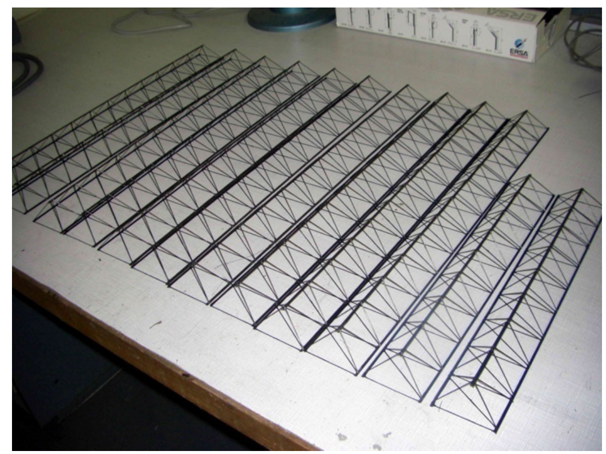




alignement structure



ALICE type support/ladders

caveat: light-weight support structure has to maintain mechanical precision < 100 µm

I.4: Simulation Results

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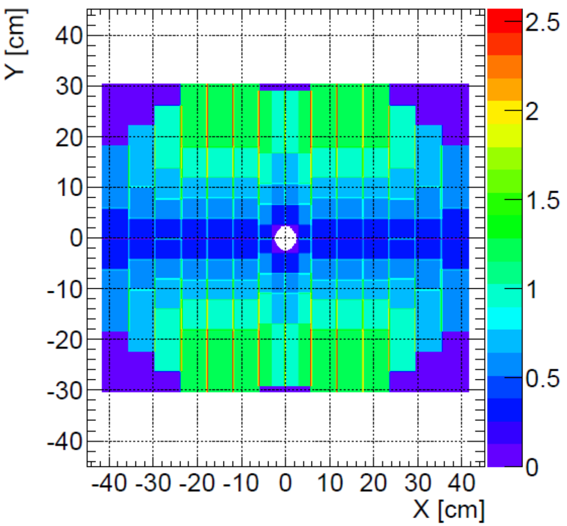
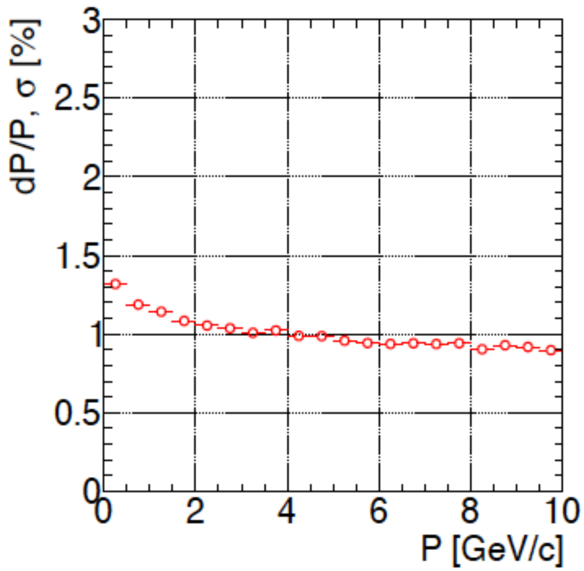
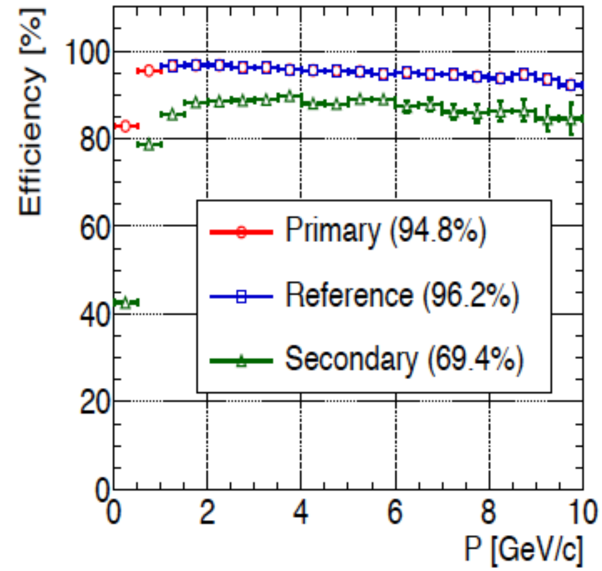
materal budget/station



momentum resolution



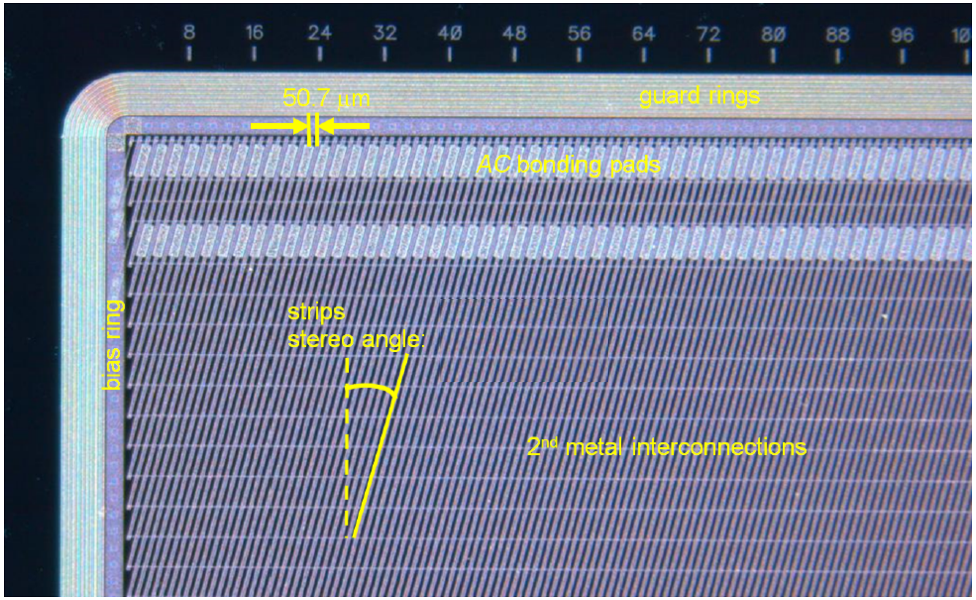
reconstruction efficiency

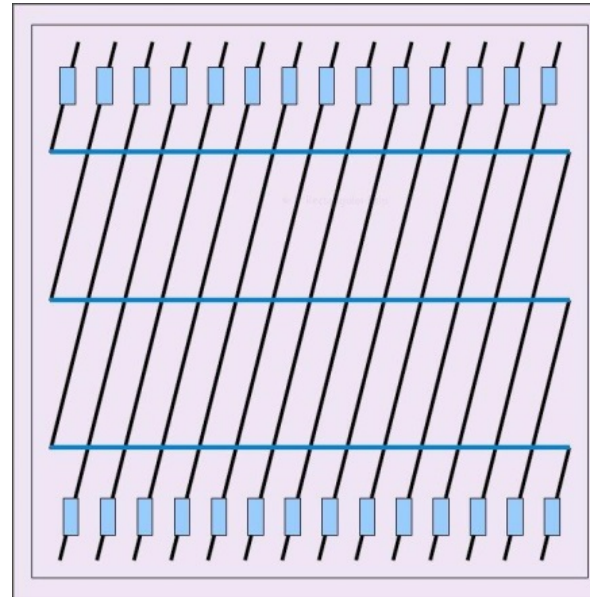


material budget ranges from 0.3% X/X_0 (only sensor) to 1% X/X_0 (sensors + cables) resulting in:

- reconstruction efficiency up to ε≈98%
- momentum resolution Δp/p≈1%

II.1: Sensors





sensor:

- n-type silicon
- 300 µm thickness
- double sided readout
- metal interconnect between strips

X/X_0 !

large number of masks, complicated production, yield?

granularity and space point resolution:

- strip pitch: 58 µm
- stereo angle between font and back strips: 7.5 °
- strip length: 2.2, 4.2, 6.2 cm

II.2: High Multiplicity Tracking & Granularity

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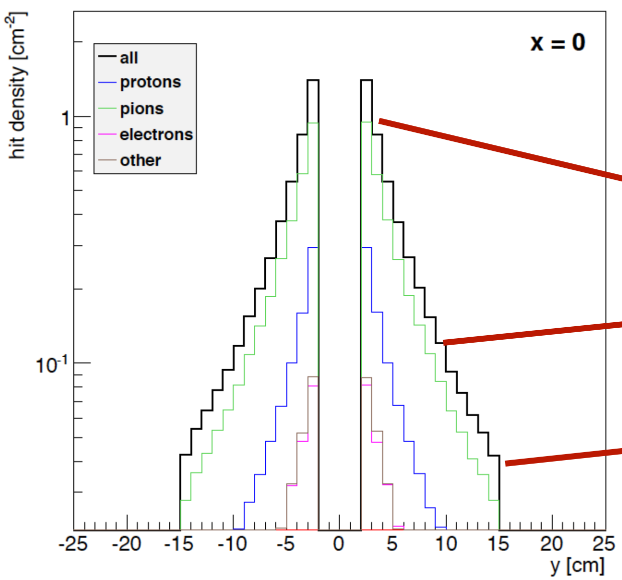
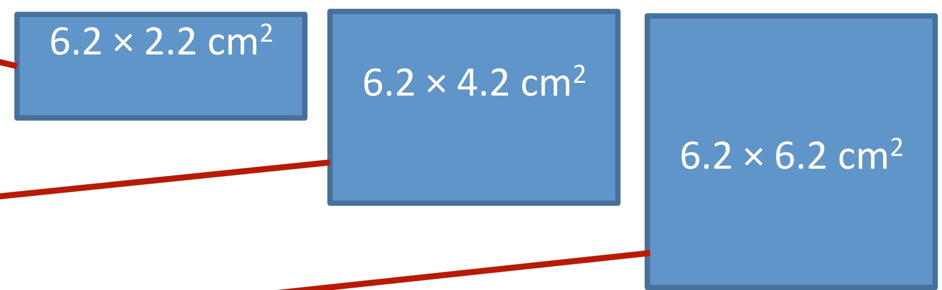
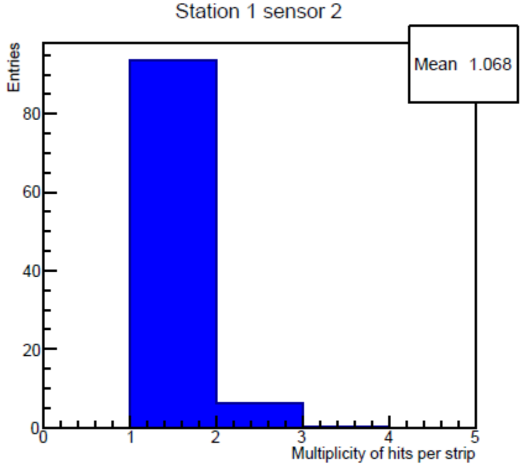


station 1

fixed target experiments have steeply falling hit densities ⇒sensor geometry has to adapted accordingly



the CBM STS features 3 different sensor sizes and daisy chained combinations ⇒ many different basic "modules"
⇒ enormous complication for simulation and production



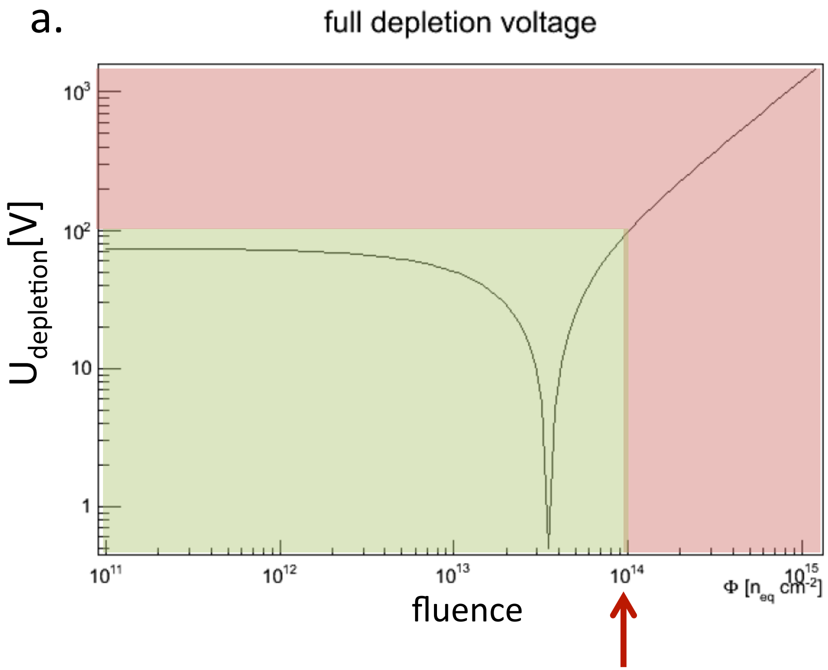
double hit probability for inner sensors below 3.6 % (7% at SIS 300) for Au+Au collisions

III.1 Rad. Hardness & Cooling

effects in high radiation environment:

a. type inversion ⇒ end-of-lifetime criterion
b. thermal runaway ⇒ keep sensors at -5°C all the time

a.



- end-of-lifetime of sensor reached at 10^{14} n_{eq}/cm^2
- 5-10 month of running at 10 MHz

b.

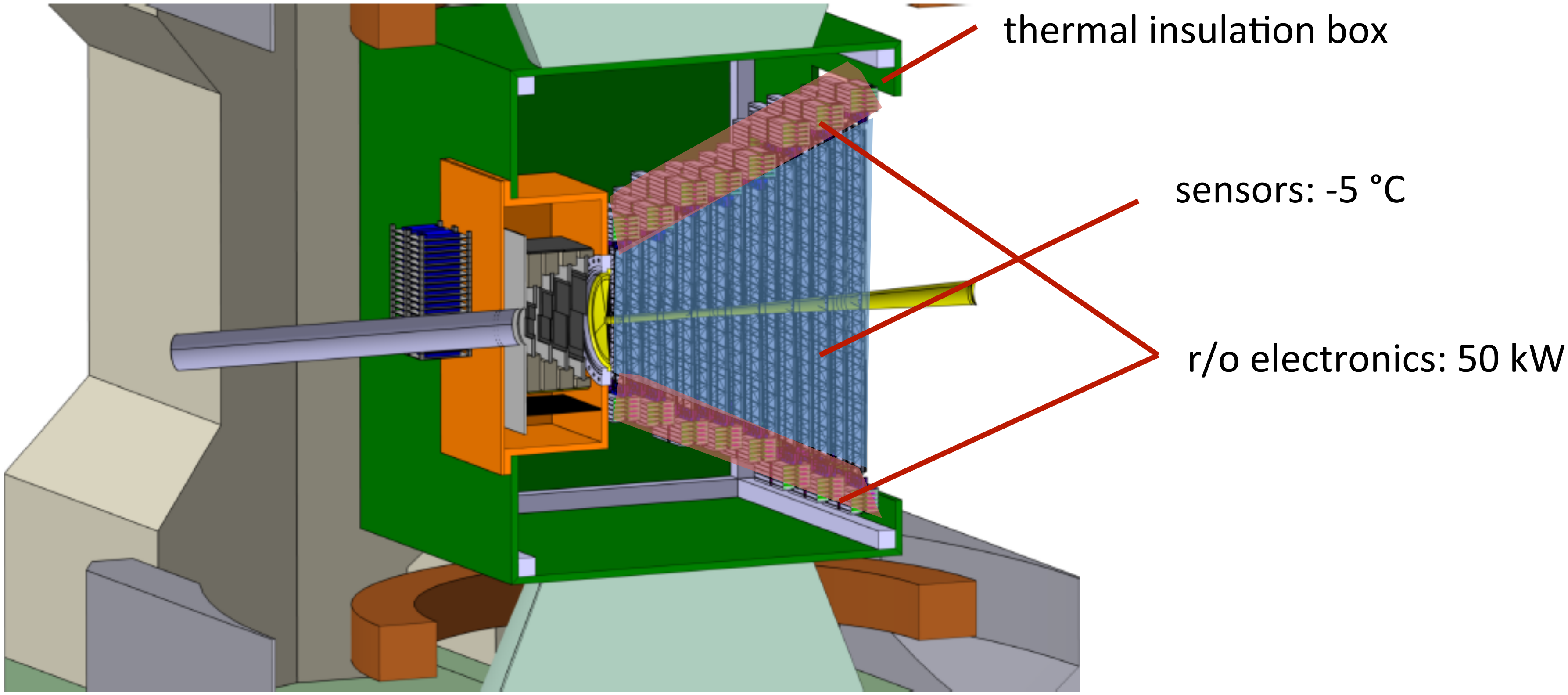
$$I_{leak} = \alpha V \Phi$$

$$I_{leak}(T) = I_{leak,293}\left(\frac{T}{293\mathrm{K}}\right)^2 \exp\left(-\frac{E_{\mathrm{gap}}(T)}{2\mathrm{k_B}}\left(\frac{1}{T}-\frac{1}{293\,\mathrm{K}}\right)\right)$$

leakage current increase with fluence f and temperature T ⇒ sensor cooling mandatory to avoid thermal runaway

III.2: Cooling

caveat: fast readout electronics produces 50 kW thermal power within insulation volume



Very efficient high power CO_2 cooling system under development to neutralize 50 kW thermal power from r/o electronics!

for comparison: CMS develops a 15 kW CO_2 cooling system for sLHC

III.1: Trigger & Readout

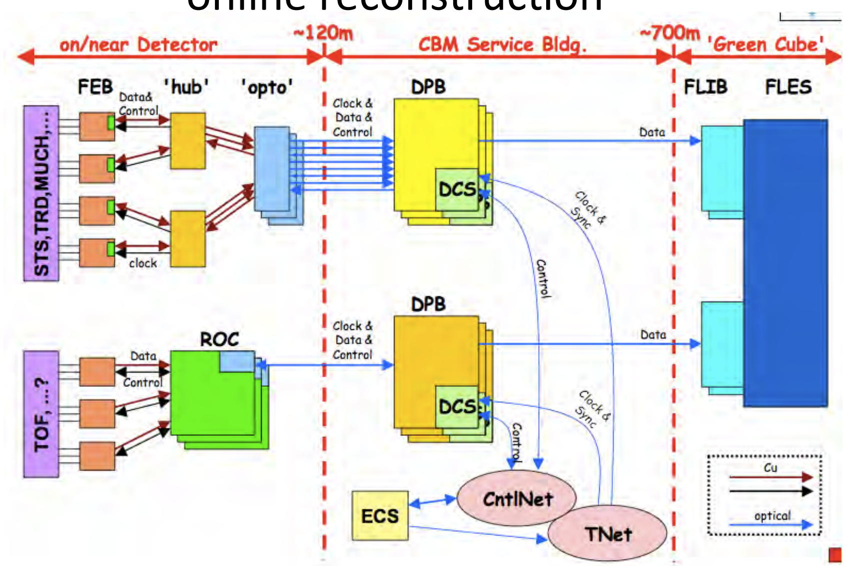
CBM will have a (quasi-) continuous beam and event rates (up to 10^7 Hz):

- trigger: no trigger
  - complex signatures for rare events (e.g. $\Omega \rightarrow$charged hadrons) difficult to implement in hardware
  - extreme event rates set strong limits to trigger latency
- therefore: purely data driven readout with time-stamped data
- raw data rate: 1 TB/s exceeds storage capacity

1 TB/s

raw data

online reconstruction

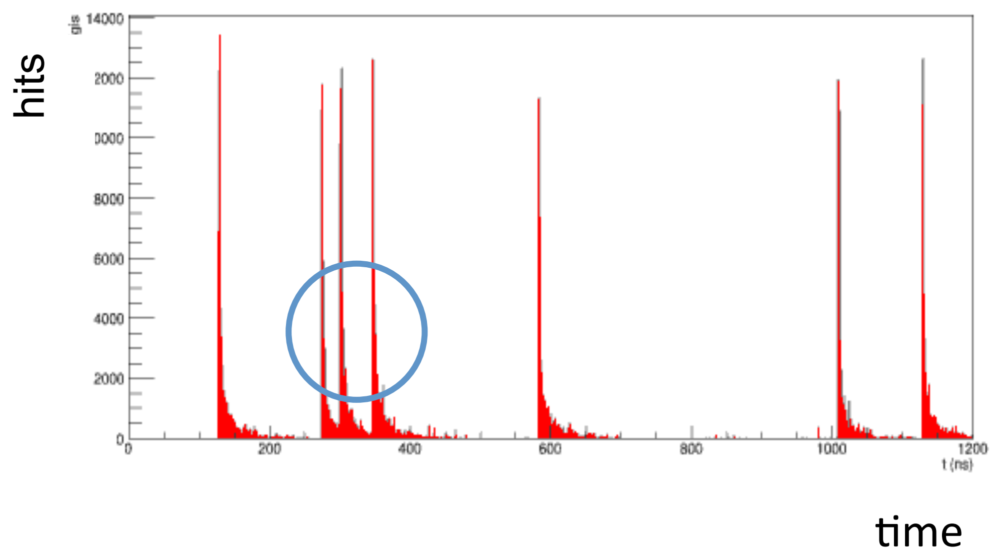


~ GB/s

to storage

III.2: Data Reduction

- data reduction and triggering is shifted entirely to software
- detector hits have (x,y,z,t) information, but no event information
- hits from different events may overlap in time
- event determination means 4D tracking (time and space points)



- though-put capacity of online computing determines detector performance

Summary & Conclusions

two examples of modern 3D-detectors:

- the ALICE TPC after upgrade (2018)
- the CBM STS at SIS100 (2018/19)

both detector aim from unprecedented rates for these detector types

- ALICE TPC 50 KHz PbPb
- CBM STS 10 MHz AuAu

the realization of these detector is only possible with a paradigm change:

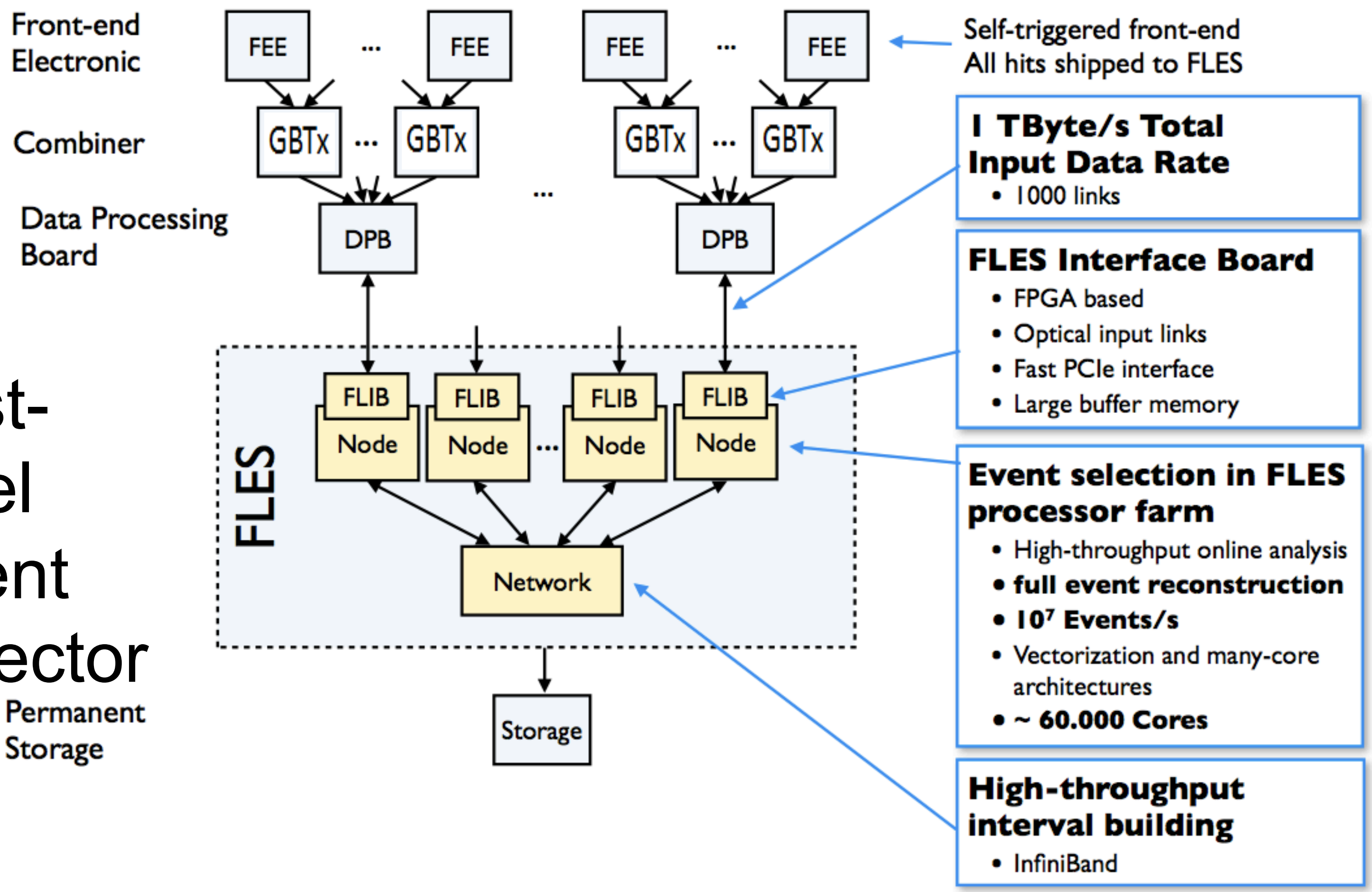
targeted performance of modern 3D-detectors is only possible with massive online-computing

high performance computing (HPC) becomes part of the detector

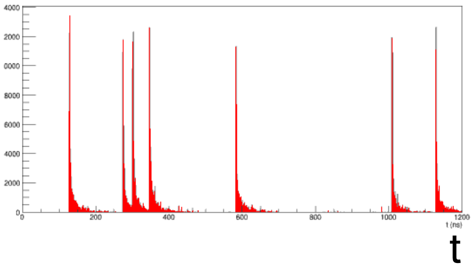
Backup slides

CBM online data flow

First-level Event Selector

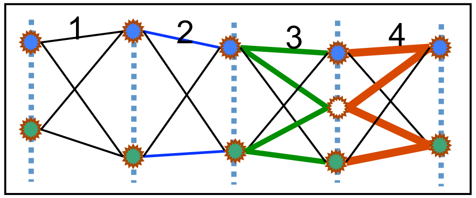


Steps of event reconstruction

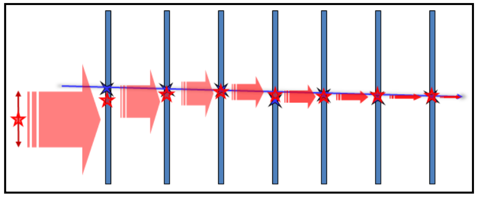


1. Time-slice sorting of detector hits:
   First step in "pre-event" definition.

2. Track finding – Cellular Automaton:
   Which hits in the detector layers belong to the same track?
   - large combinatorial problem
   - well to be parallelized
   - applicable to many-core CPU/GPU systems



3. Track fitting – Kalman Filter:
   Optimization of the track parameters.
   - recursive least squares method, fast



4. Event determination
   Which tracks belong to same interaction?

5. Particle finding:
   Identify decay topologies and other signatures.