Silicon Pixel Detector
in
High Energy Physics Experiments

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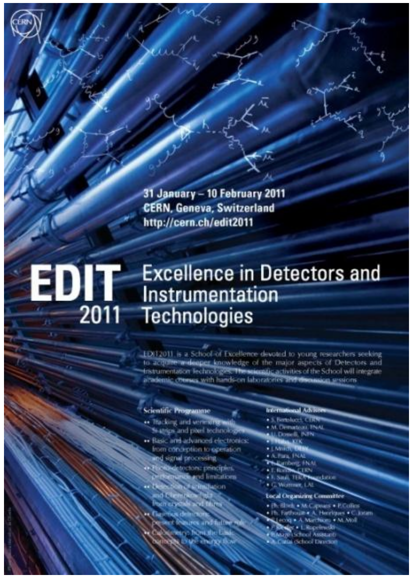

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EDIT 2011 Excellence in Detectors and Instrumentation Technologies

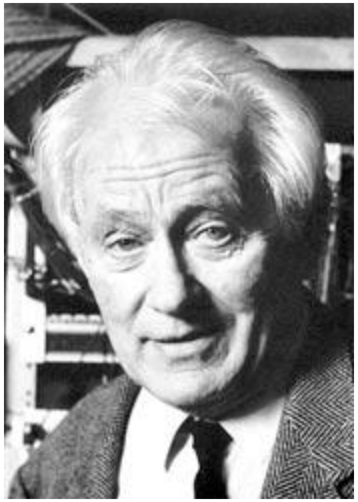
Outline

- Introduction
- Pixel detector for HEP experiment
- The Pixel Tracking telescope of the NA57 fixed target experiment at the CERN SPS
- The ALICE Silicon Pixel Detector at the CERN LHC

Why silicon detectors in HEP?

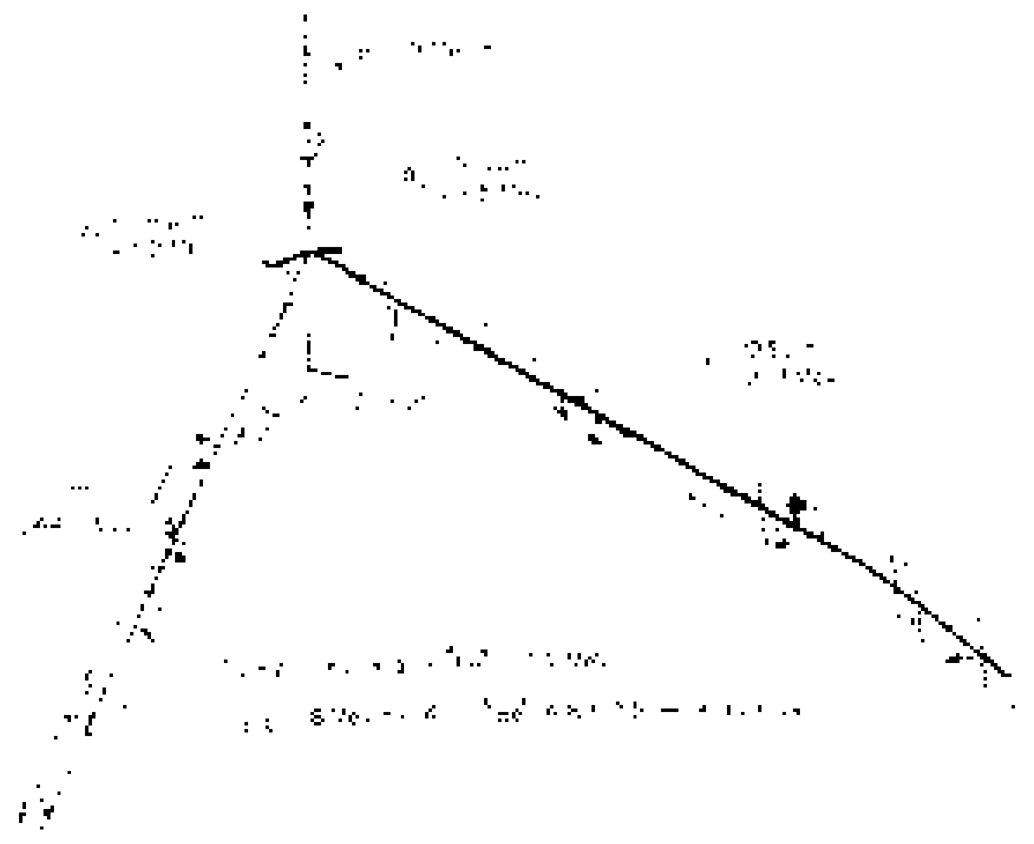
- Physicists always want to ‘see’ elementary particles
  - Track particles without disturbing them
  - Determine position of primary interaction vertex and secondary vertex decays

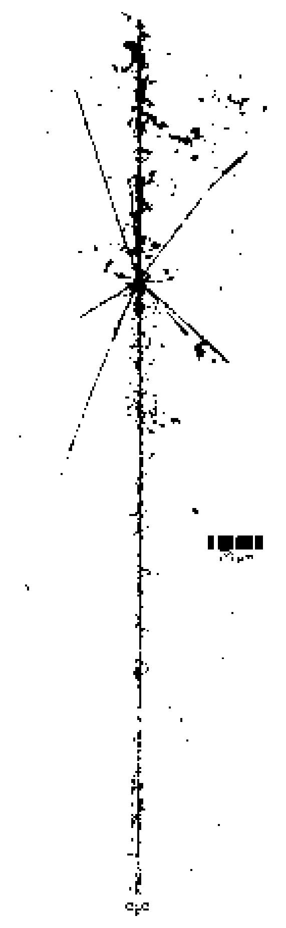
- During the years different techniques were developed to visualize the tracks of particles:
  - nuclear emulsion
  - cloud chamber
  - bubble chamber
  - spark chamber
  - streamer chamber
  - proportional gas detector
    - MWPC, Drift chambers, Straw tubes, TPC, etc. → Charpak 1968



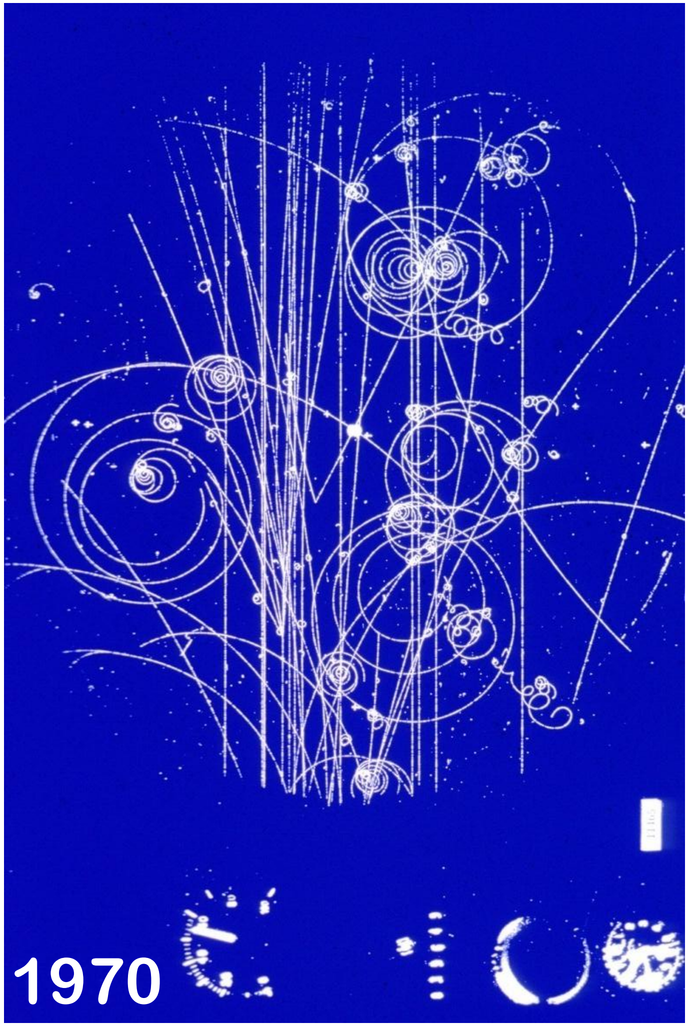
Nobel prize in 1992

Nuclear emulsion events

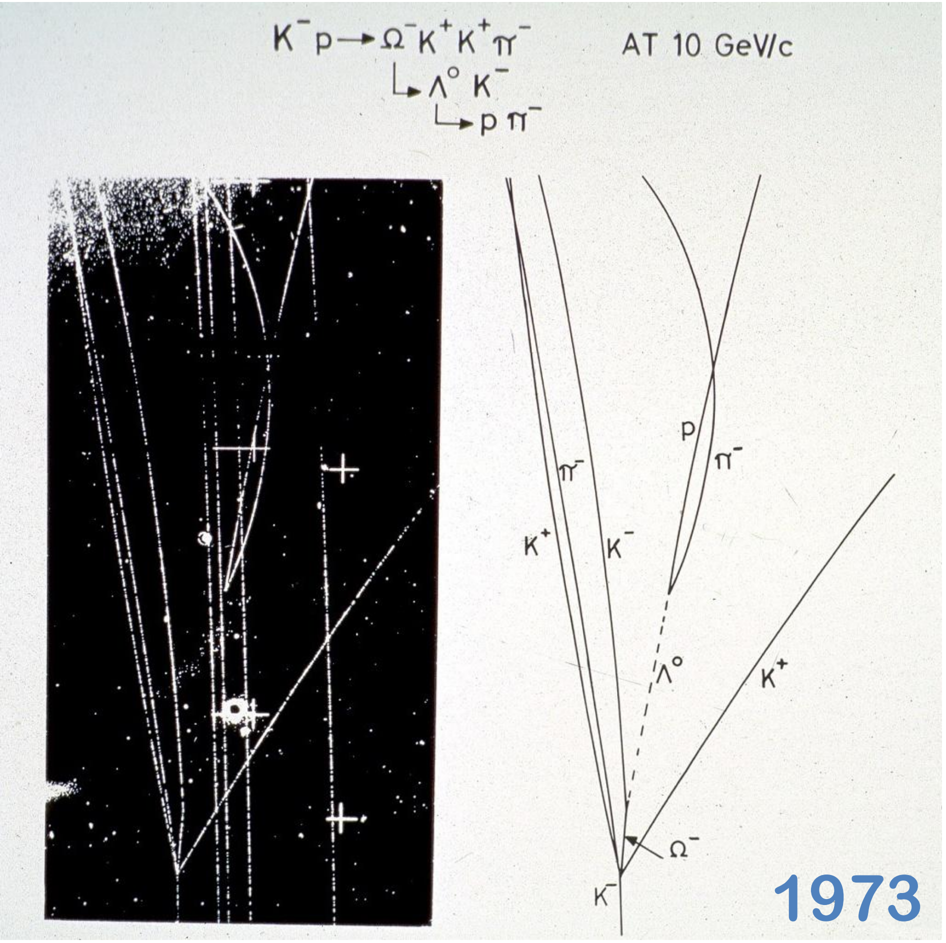




Bubble chambers

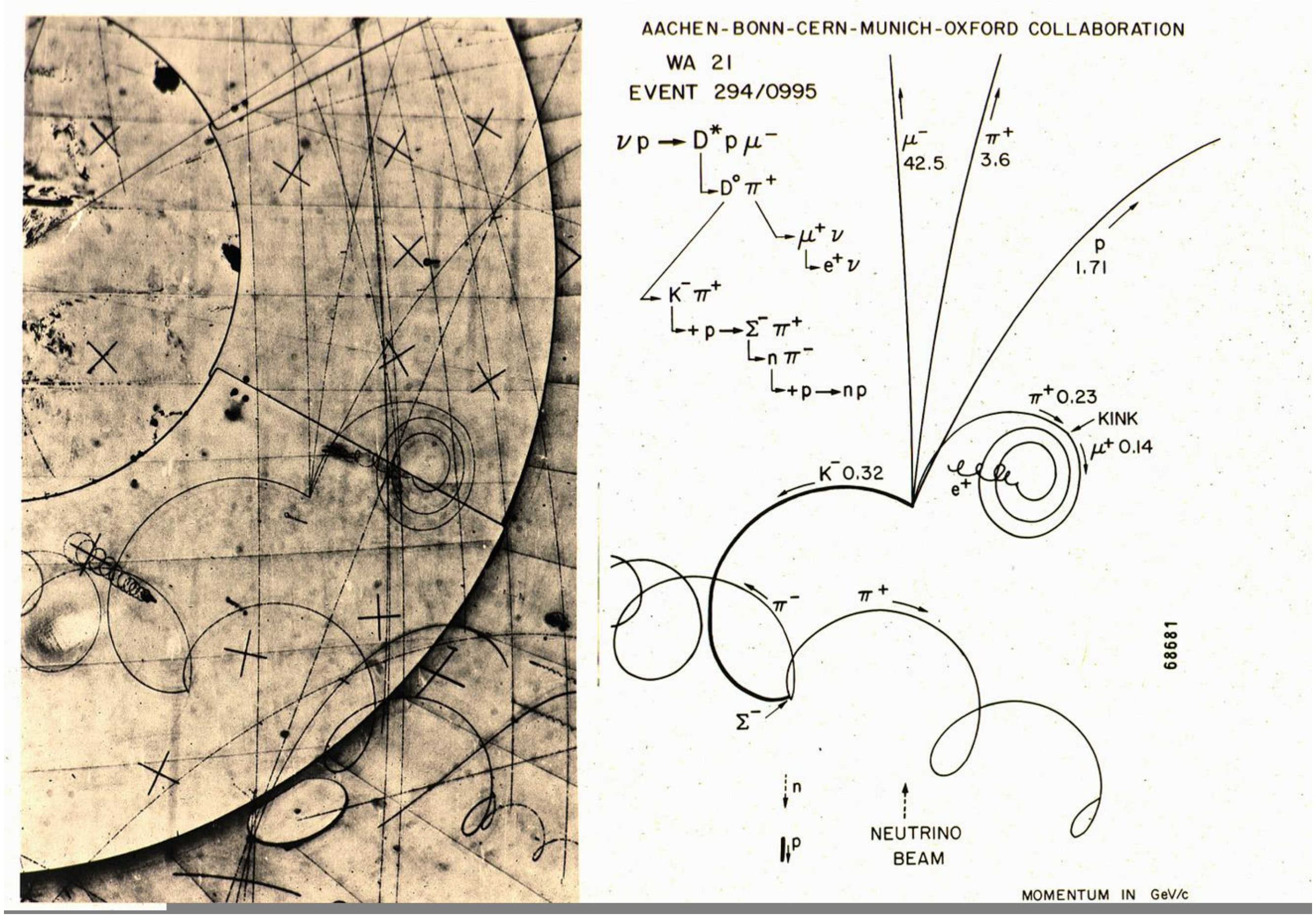


30 cm hydrogen bubble chamber (CERN)



Ω^- in 2-m CERN hydrogen bubble chamber

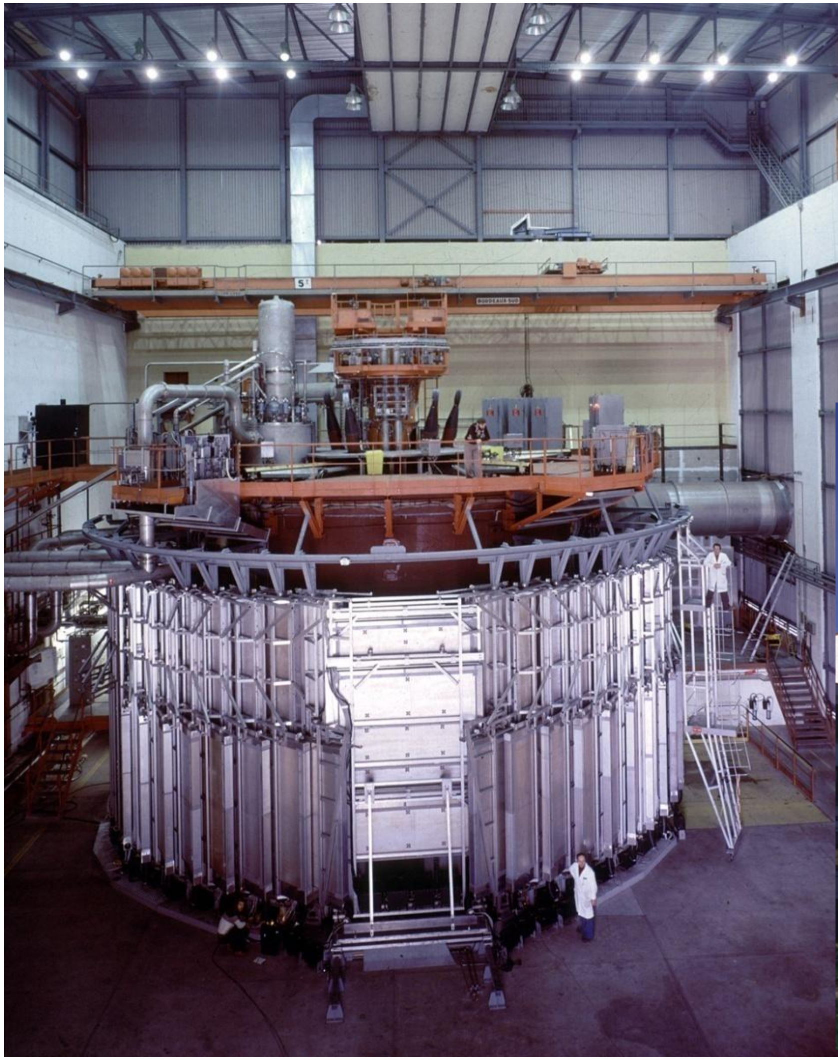
Bubble chambers



1978

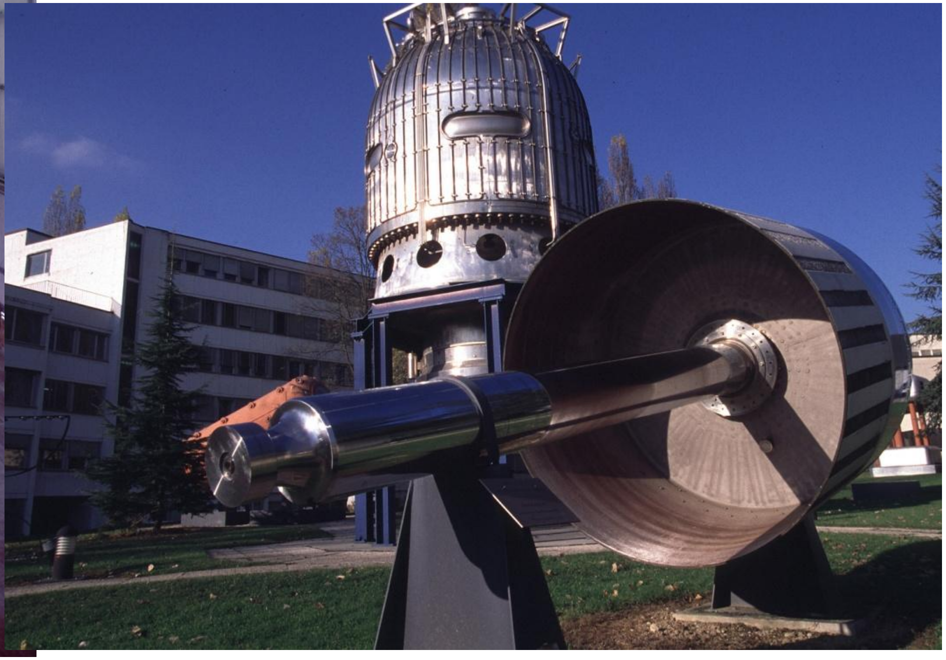
D* in BEBC hydrogen bubble chamber

Big European Bubble Chamber

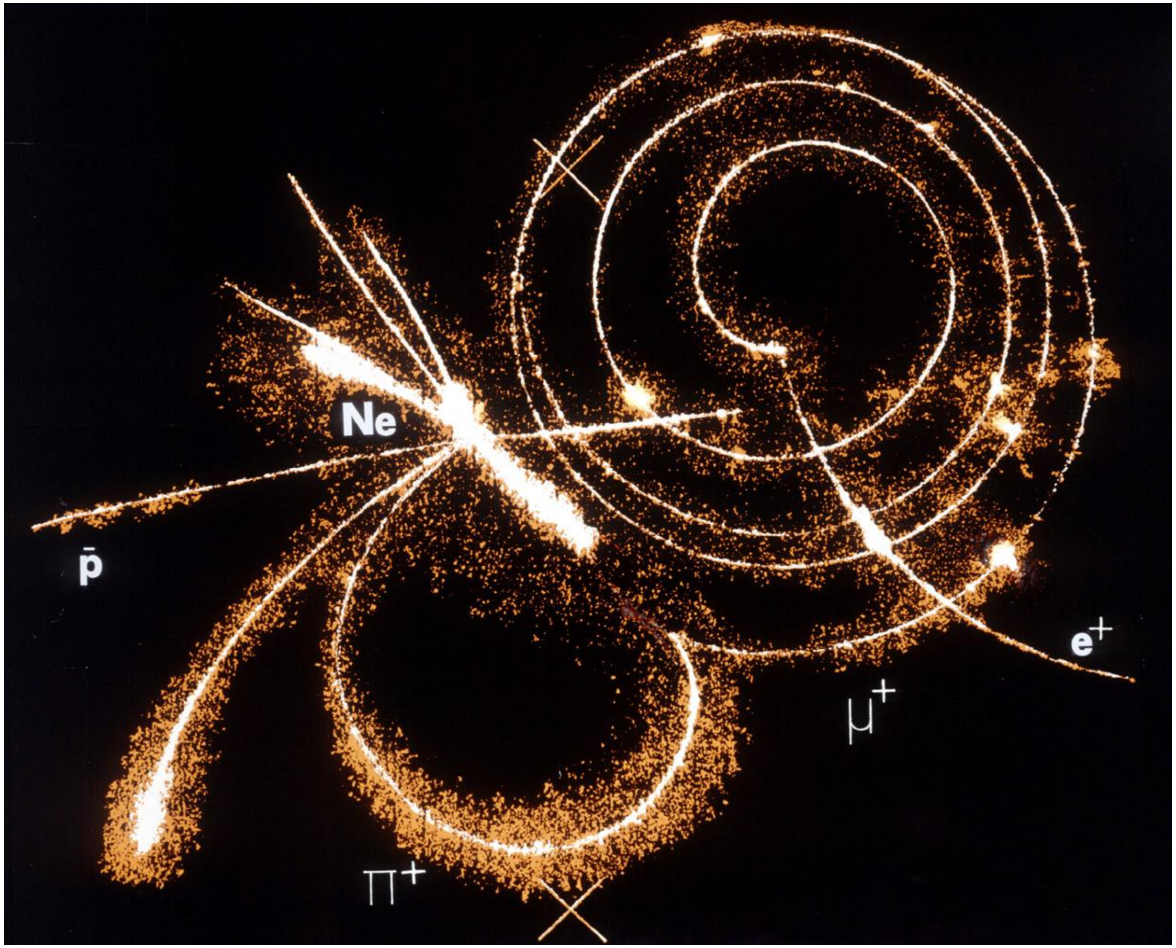


BEBC in 1977

and in 1997



Streamer chambers

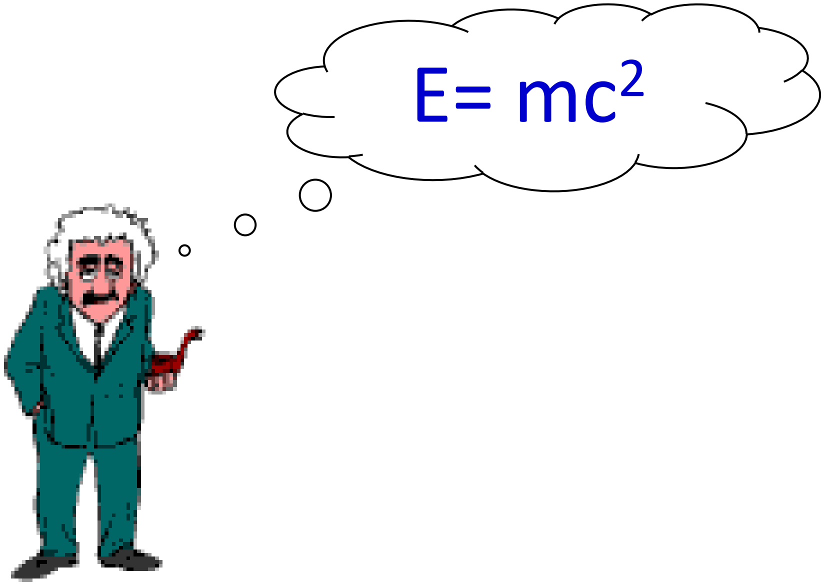


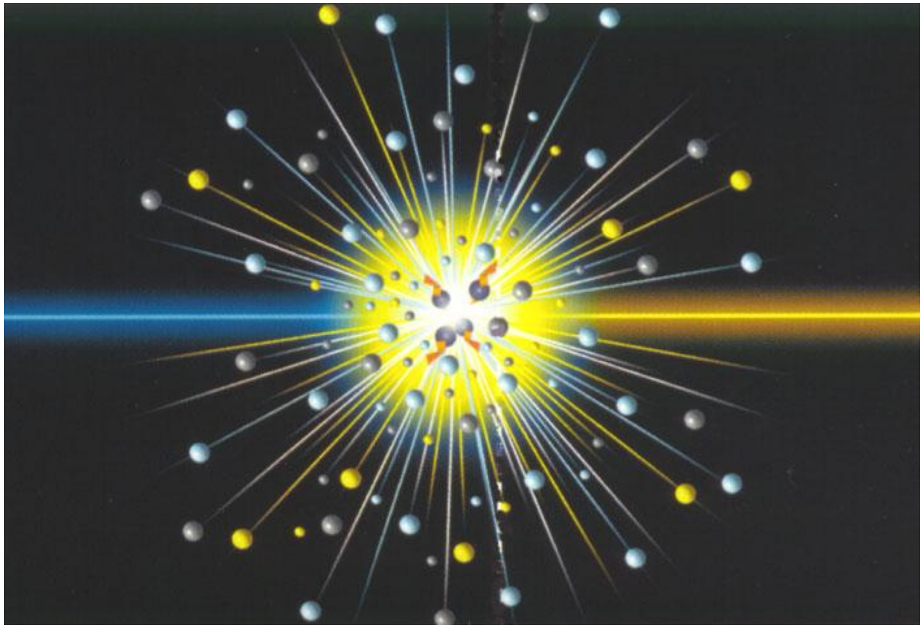
1984

$\pi^+ \to \mu^+ \to e^+$ decay in streamer chamber

Why silicon detectors in HEP?

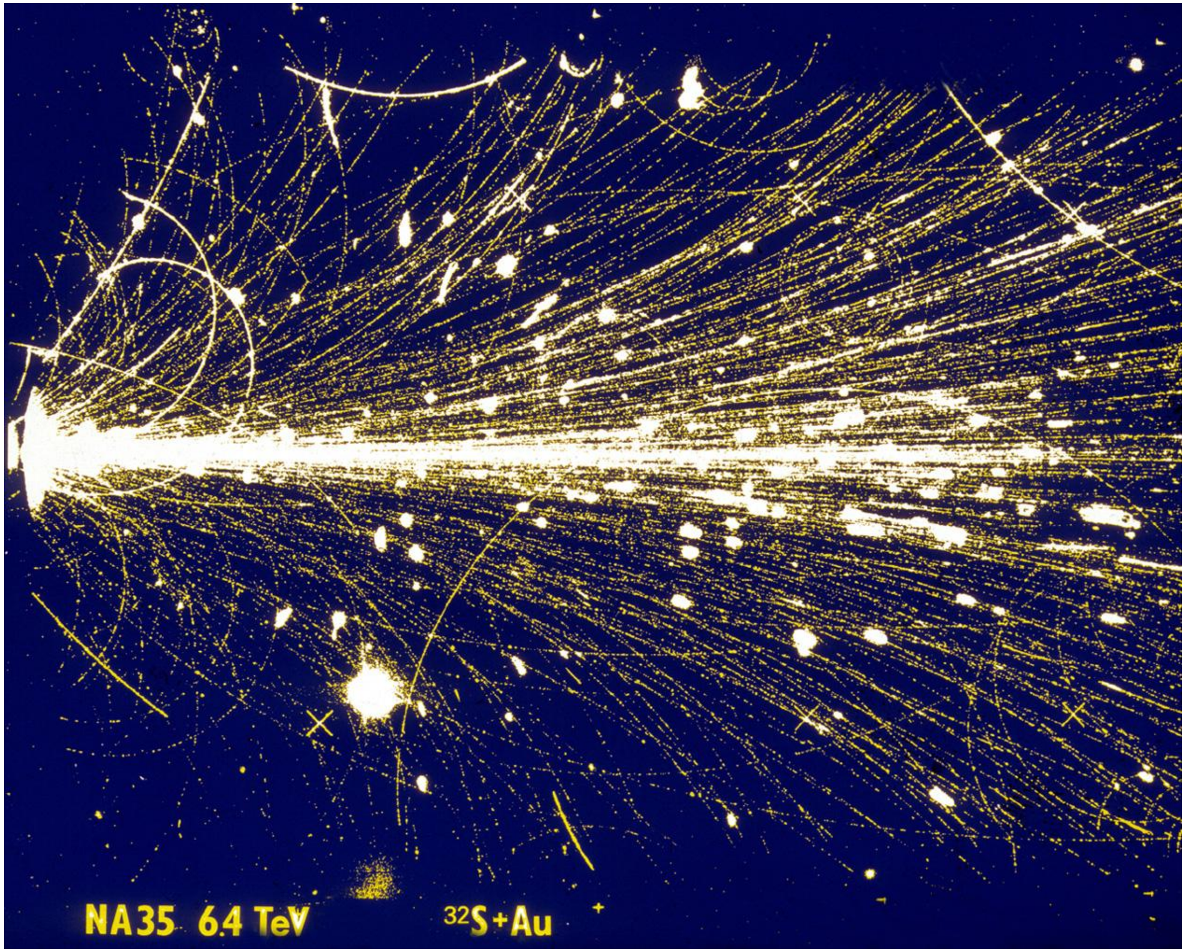
- With the increasing energy available in the collision the emphasis in the HEP experiments shifted to tracking and vertexing capabilities





- Almost all tracking detectors listed before have been abondoned except proportional gas detectors
  - Limited beam intensity due to sensitive time, limited high statistics due to dead time and thus accessible cross-section, limited space resolution, not easy operation

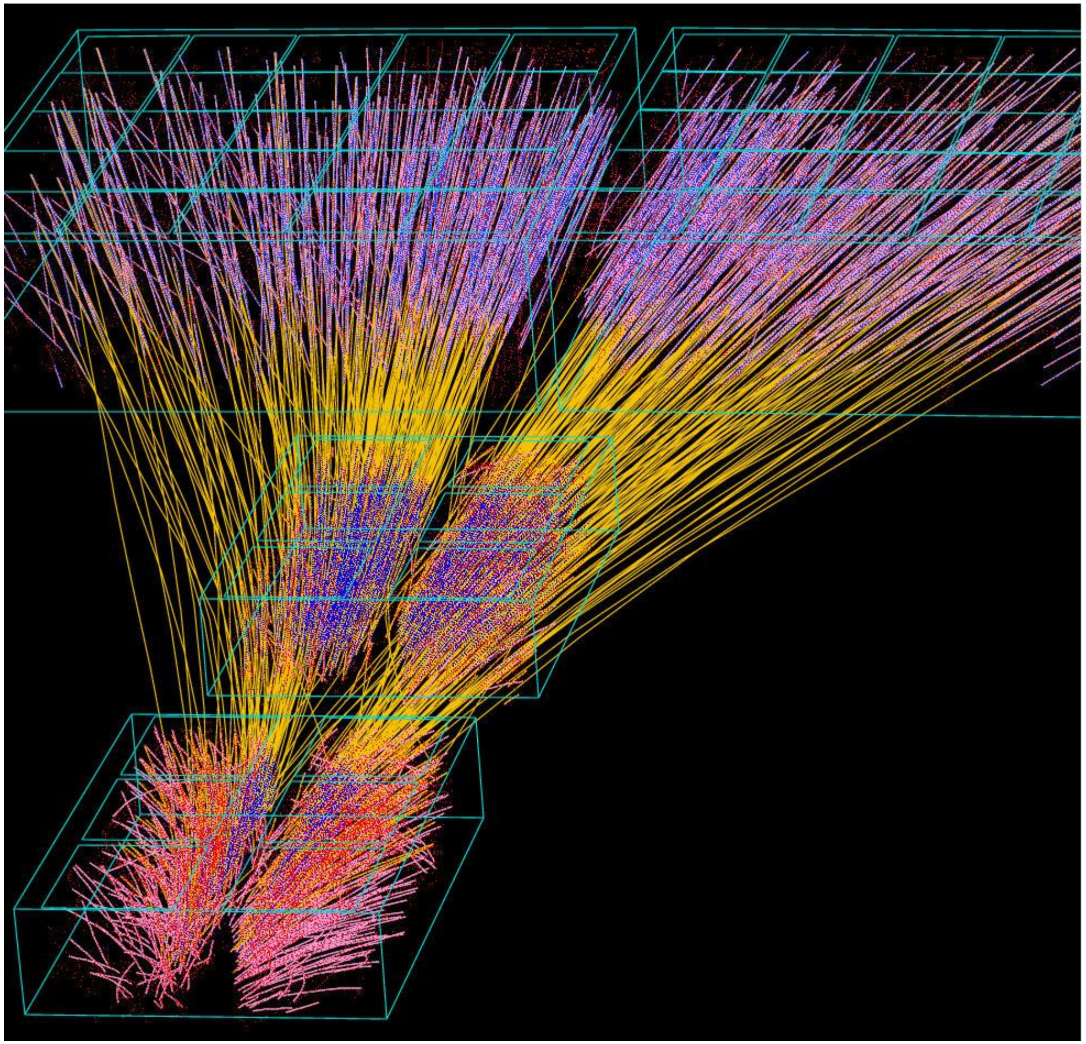
Streamer chambers



July 1991

6.4 TeV Sulphur - Gold event (NA35)

Time Projection Chambers



160 A GeV/c Lead - Lead event (NA49)

Silicon Position Sensitive Detector

- Main features of silicon detectors:
  - Fine granularity → very accurate position resolution
  - Small amount of energy for signal quanta → large signal
  - Thin → close to interaction point
  - Low mass → minimize multiple scattering

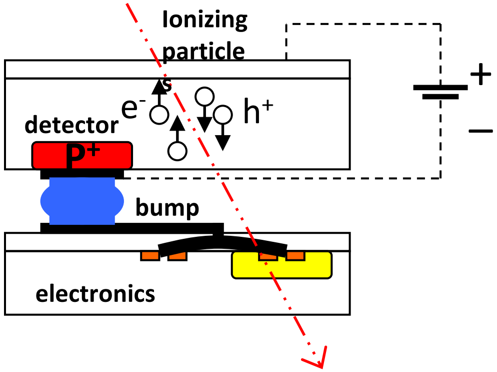
- True two dimensional detectors, like Silicon Pixel, are much robust in high particle density environment

☞ In most of the modern High Energy Physics experiment the detector closest to the interaction point is based on silicon pixel devices.

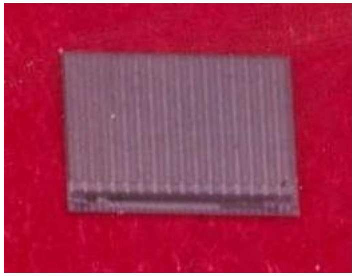
OMEGA-ION pixel detector

- In 1992 the first fully operational hybrid silicon micropattern detector was succesfully tested in a fixed target experiment environment
  - WA94 heavy ion experiment at the OMEGA spectrometer of the CERN SPS
  - WA94 predecessor of the WA97/NA57 heavy ion experiment

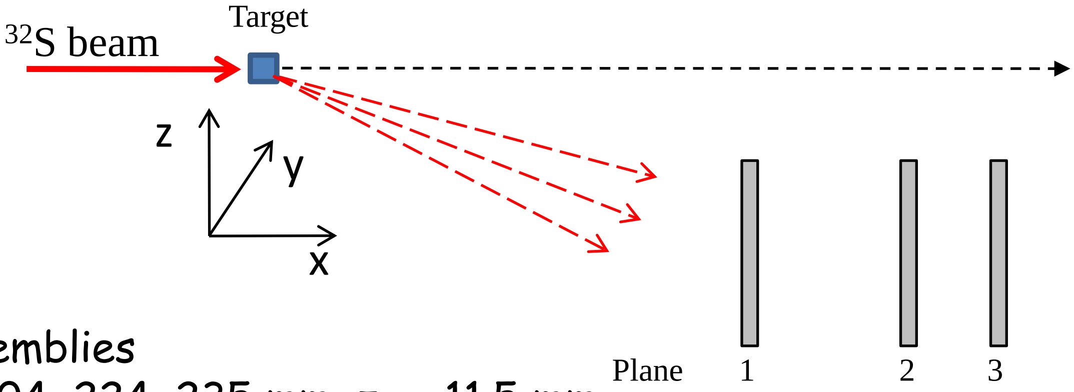
(ref. **A hybrid silicon pixel telescope tested in a heavy ion experiment**”, **Nucl. Instr. and Meth. A 332 (1993) 188-201)**



- OMEGA-D pixel detector
  - CERN R&D 19 Collaboration
  - 16 columns x 63 rows
  - cell size 500 μm x 75 μm
  - overall sensitive area 8 x 4.7 mm^2
  - binary readout

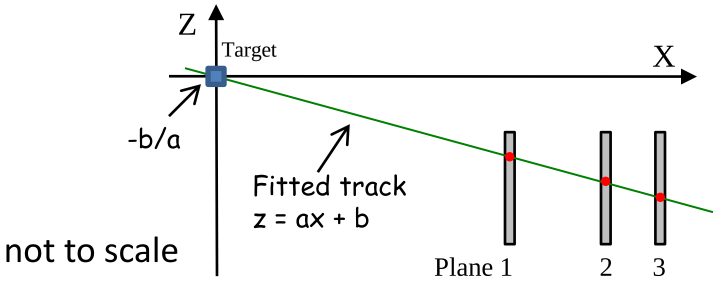


- Test environment
  - 1.8 T magnetic field
  - SS interaction
  - 5 x 10^5 ions/spill
  - Flat top 5.1 s, duty cicle 19.2 s
  - Pixel telescope: 3 single chip assemblies downstream the target: x = 204, 224, 235 mm, z = -11.5 mm

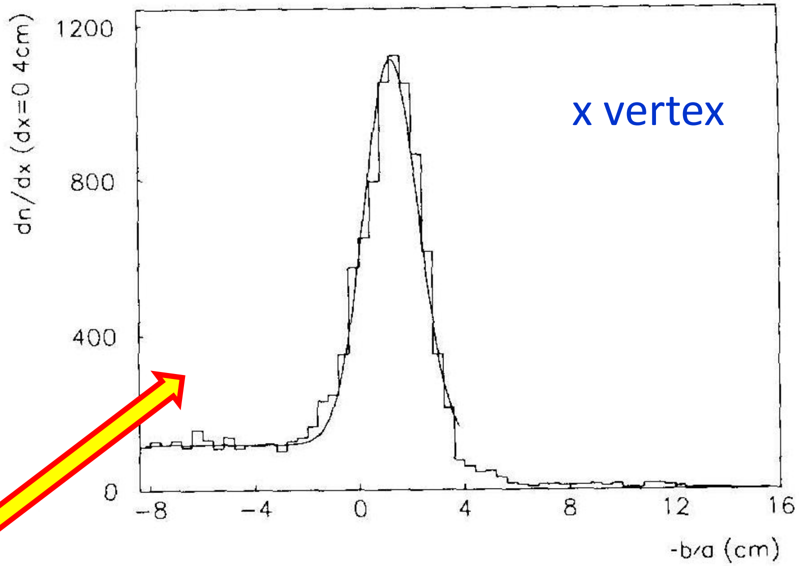


not to scale

OMEGA-ION pixel detector

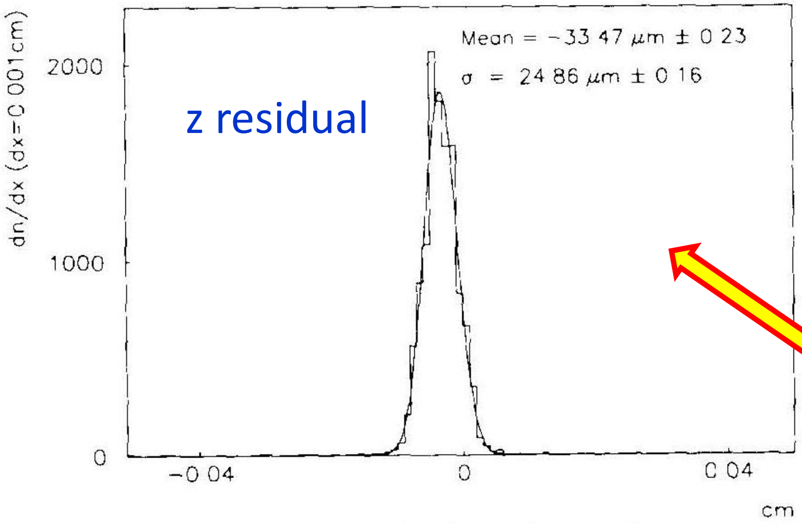


-b/a represents the intercept along the beam axis



Distribution of the intercept between fitted tracks and the axis z = 0

☞ The accumulation in the target region proves that tracks are coming from physical interaction



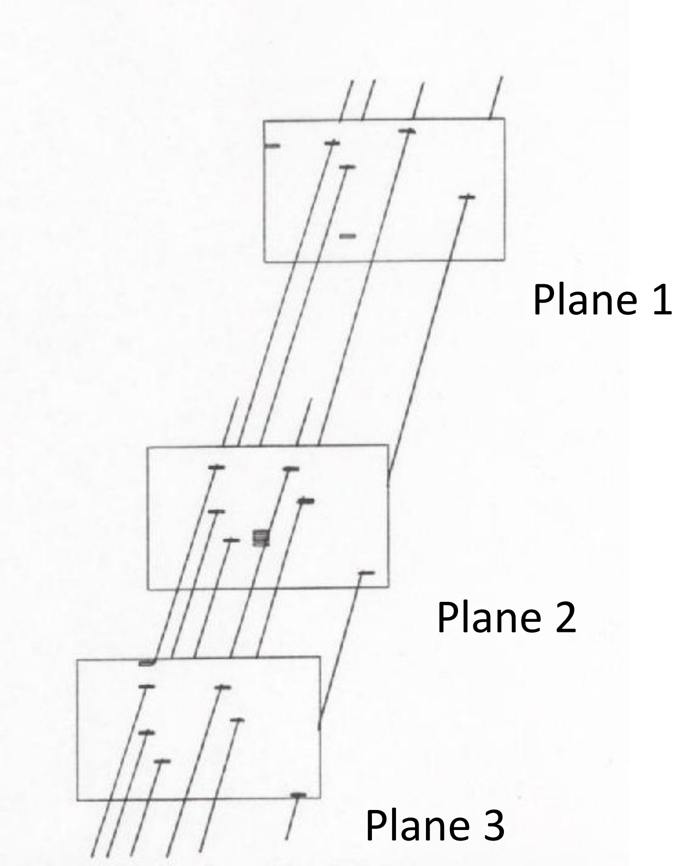
Distribution of the Δz residuals

☞ Mean value -33mm residual misalignment

☞ σ ≈ 25 μm is the space point accuracy

(expected 75μm pitch / (2 x √3) = 22μm)

OMEGA-ION Pixel Detector



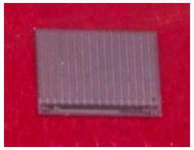
A relatively high multiplicity event in which 4 tracks are crossing all 3 detector planes (≈32 mm^2 each) and 2 more tracks appear in both downstream detectors

☞ Such multiplicities are hard to deal with in projective detectors.

Principle of detector design

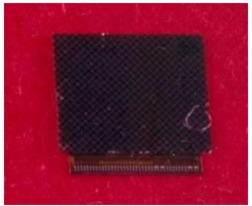
- In the first half of the '90s, CERN R&D19 Collaboration developed two generations of pixel detector suitable for fixed target experiment, namely Omega2 and Omega3

- How can we build an experimental apparatus for a High Energy Physics experiment from these device?



Omega2:

- 16 col x 63 row
- cell size 500 x 75 μm^2
- overall sensitive area 8.0 x 4.7 mm^2

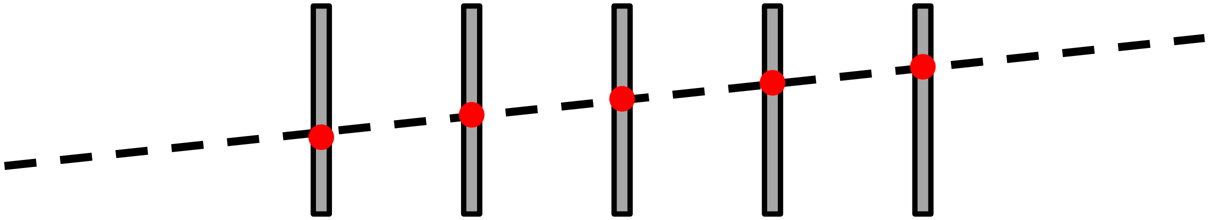


Omega3:

- 16 col x 127 row
- cell size 500 x 50 μm^2
- overall sensitive area 8.0 x 6.4 mm^2

Tracking Detectors

- High energy charged particles may produce enough interactions to give a detectable signal in a thin detector and still retain enough of its energy to be detected many more times in subsequent detectors

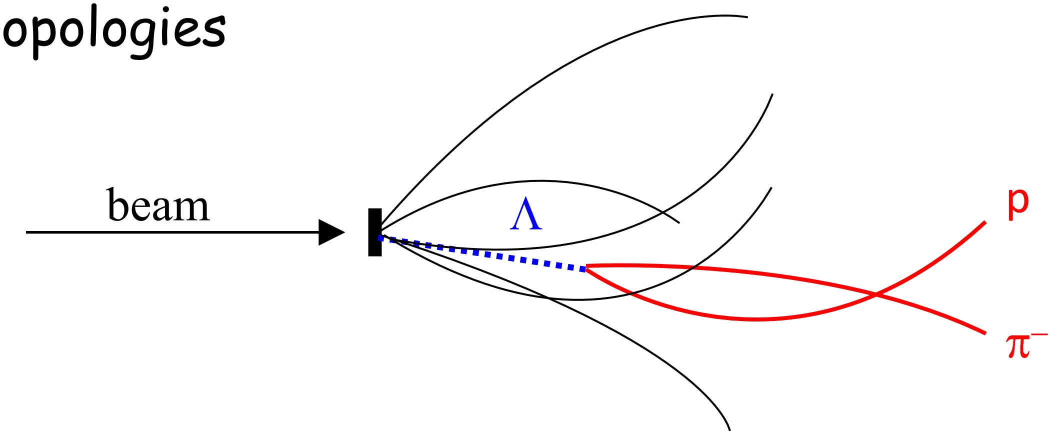


- Tracking detectors allow to determine the path of the particles
  - Charged particles of sufficiently high energy may be detected many times along their path and be tracked in considerable detail.
- The job of the experimental apparatus is to measure the time of the interaction t and/or the vector momenta **p** and/or masses M of the particles emitted in the primary interaction of a beam on a fixed target or beam-beam in a collider.

Experiment CERN WA97/NA57

- Physics:
  - Study of the strange and multi-strange particle production in Pb-Pb collisions at the CERN SPS

- Experimental technique:
  - high granularity silicon pixel tracker at central rapidity $y_{cm} \sim 0$
  - detect strange and multi-strange particles by reconstructing weak decay topologies



☞ The long lifetime of weakly decaying particles allows to separate the secondary decay products from the much more numerous primary collision products, drastically reducing the combinatorial backgrounds

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Experiment CERN WA97/NA57

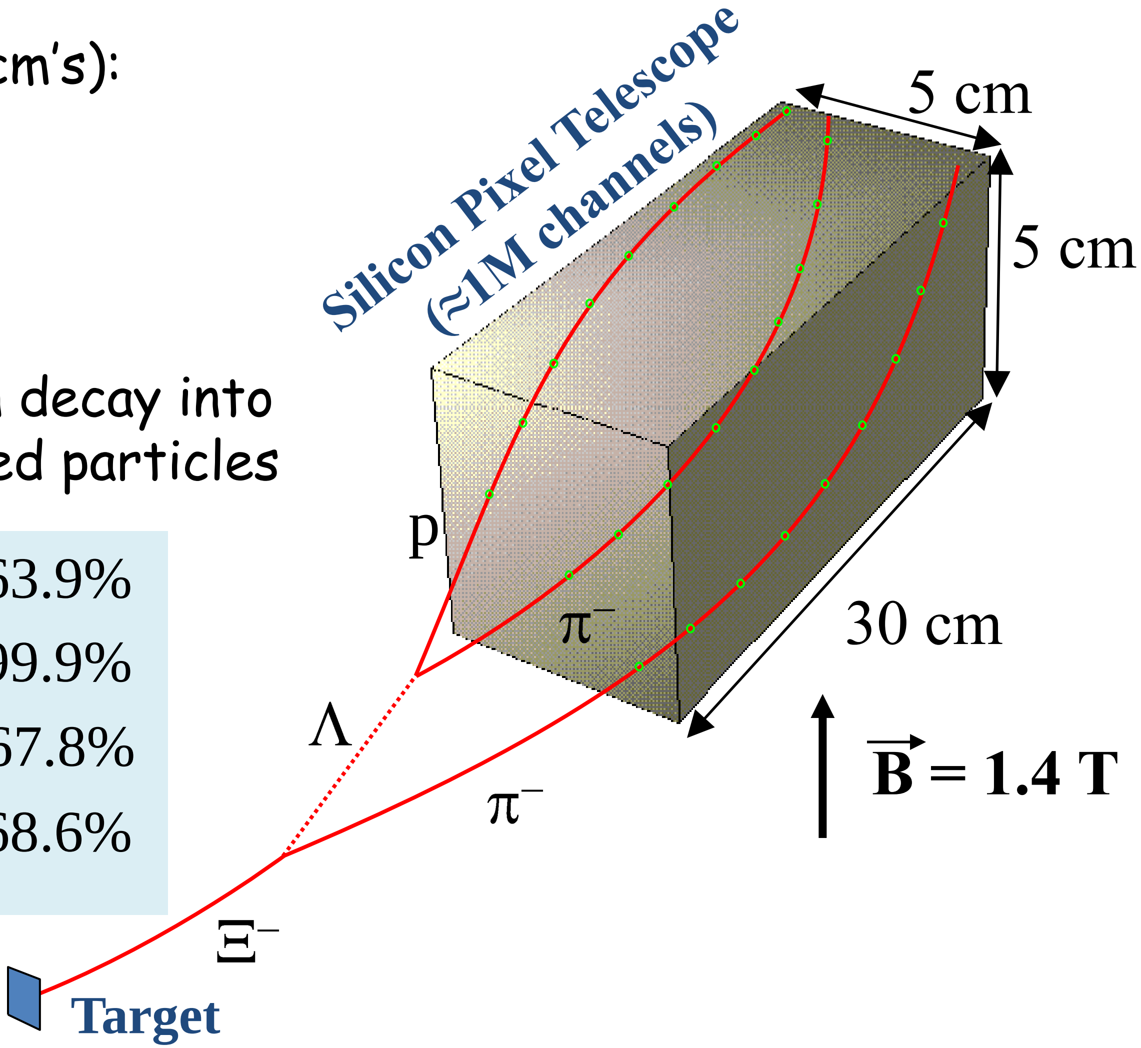
- There are 35 strange baryons listed in the PDG summary tables
- Only 6 decay weakly (cτ ~ cm's):

$\Lambda, \Sigma^+, \Sigma^-$	(sqq)
Ξ^0, Ξ^-	(ssq)
Ω^-	(sss)

- Only 3 of them plus K^0_S can decay into final state with only charged particles

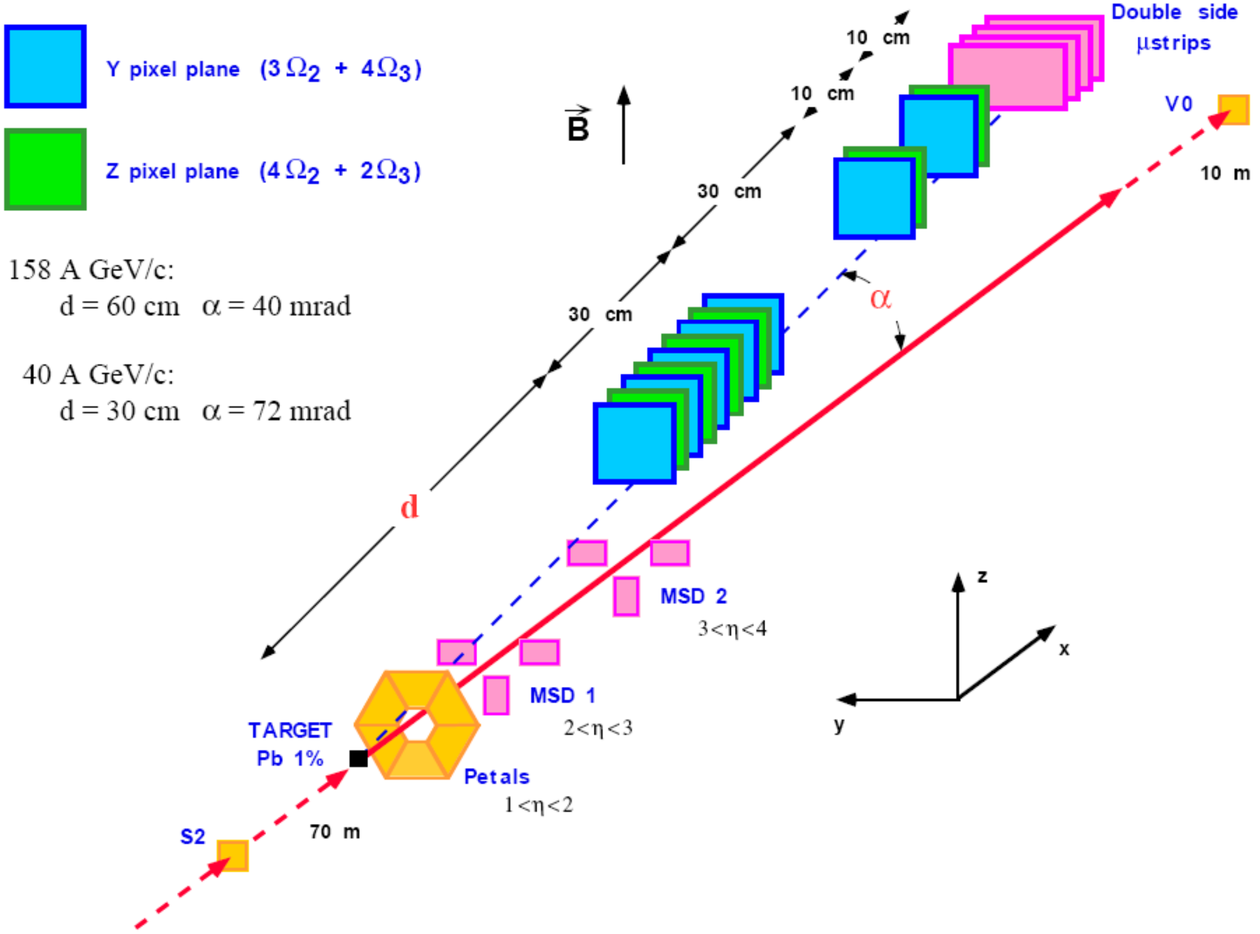
$\Lambda \dashrightarrow p + \pi^-$	BR = 63.9%
$\Xi^- \dashrightarrow \Lambda + \pi^-$	BR = 99.9%
$\Omega^- \dashrightarrow \Lambda + K^-$	BR = 67.8%
$K^0_S \dashrightarrow \pi^+ + \pi^-$	BR = 68.6%

plus c.c.



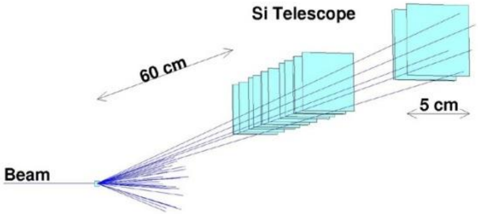
NA57 Set-up

- Silicon Pixel Tracking Telescope:
  - 13 logical planes of Omega 2 and Omega 3 hybrid silicon pixel detector

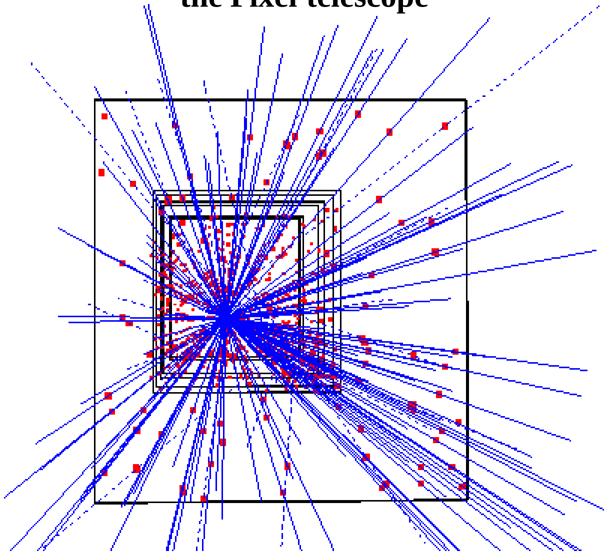


158 A GeV/c:
d = 60 cm α = 40 mrad

40 A GeV/c:
d = 30 cm α = 72 mrad

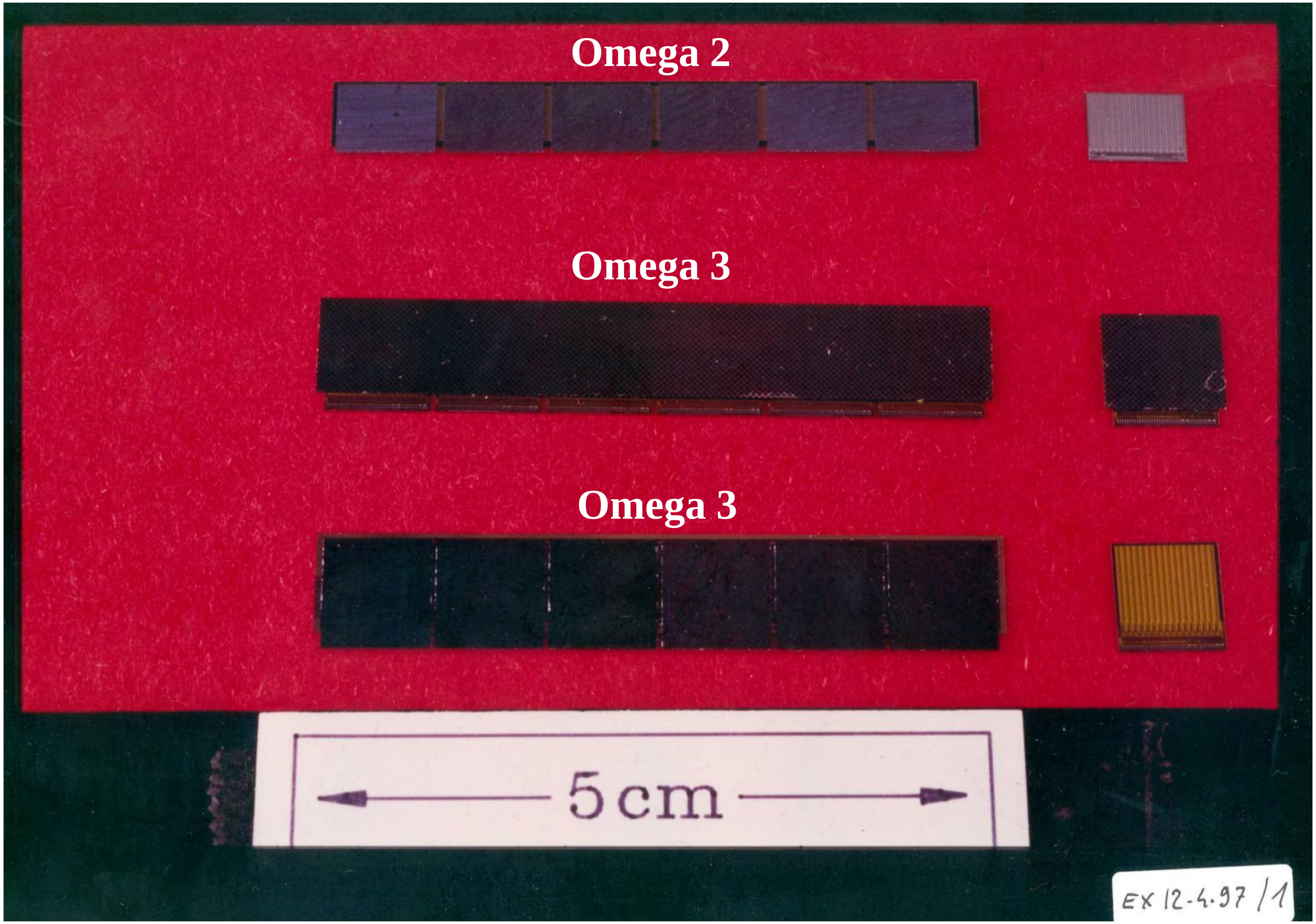


153 tracks reconstructed through the Pixel telescope

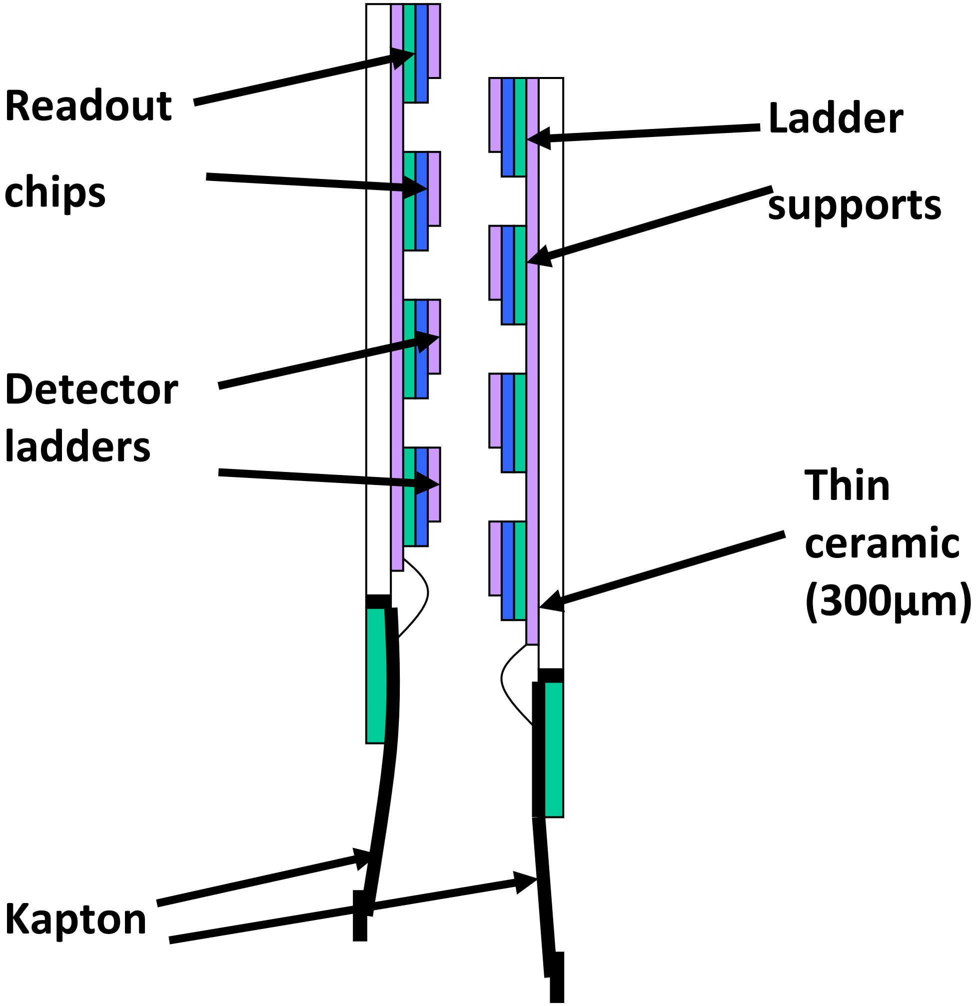


Omega2 and Omega3 ladders

A ladder consists of 6 front-end chips bump-bonded to one sensor tile



NA57 Pixel logical plane



Omega 3 arrays and Logical plane

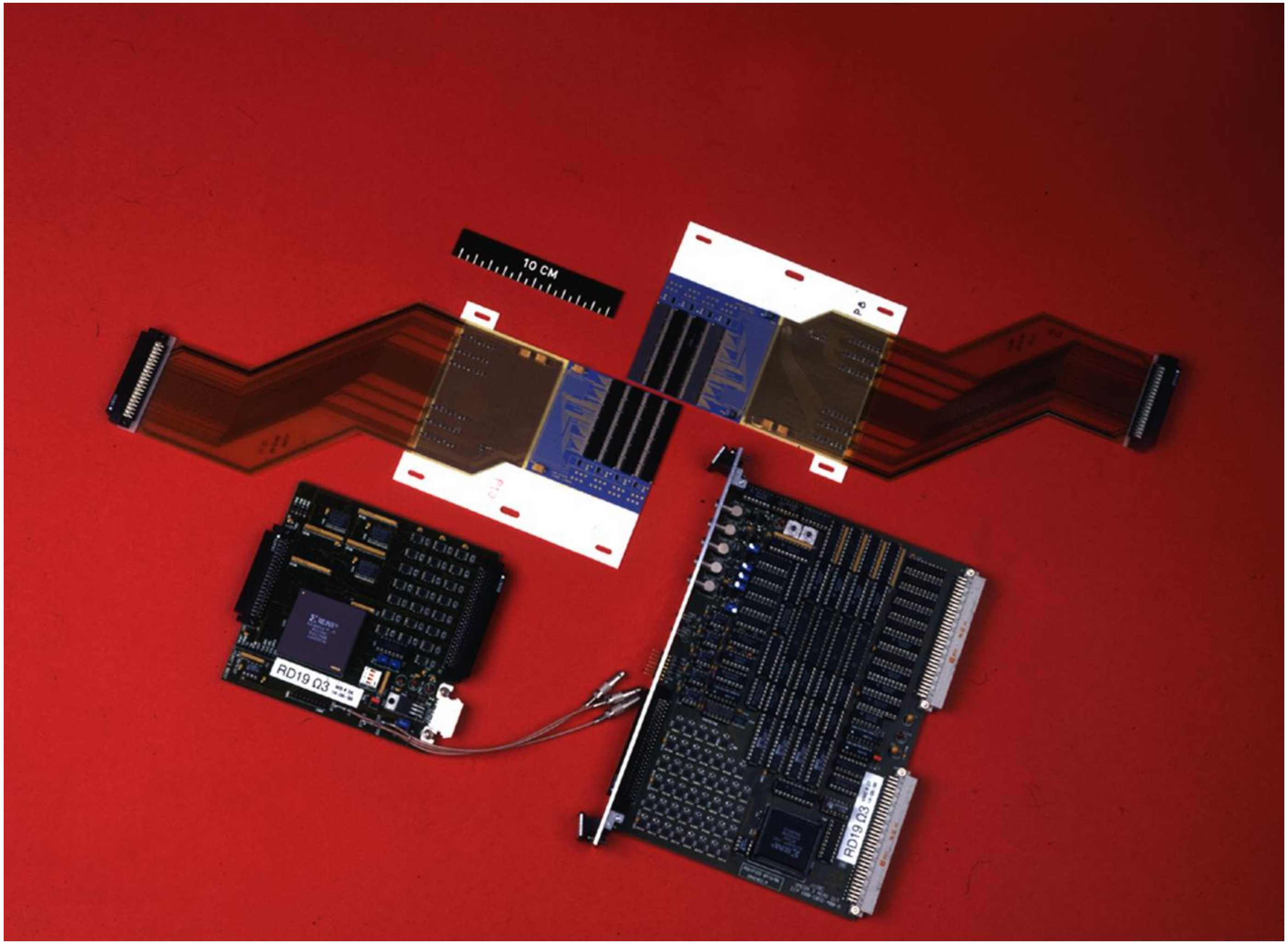
(Omega 2 arrays contain 6 ladders instead of 4)

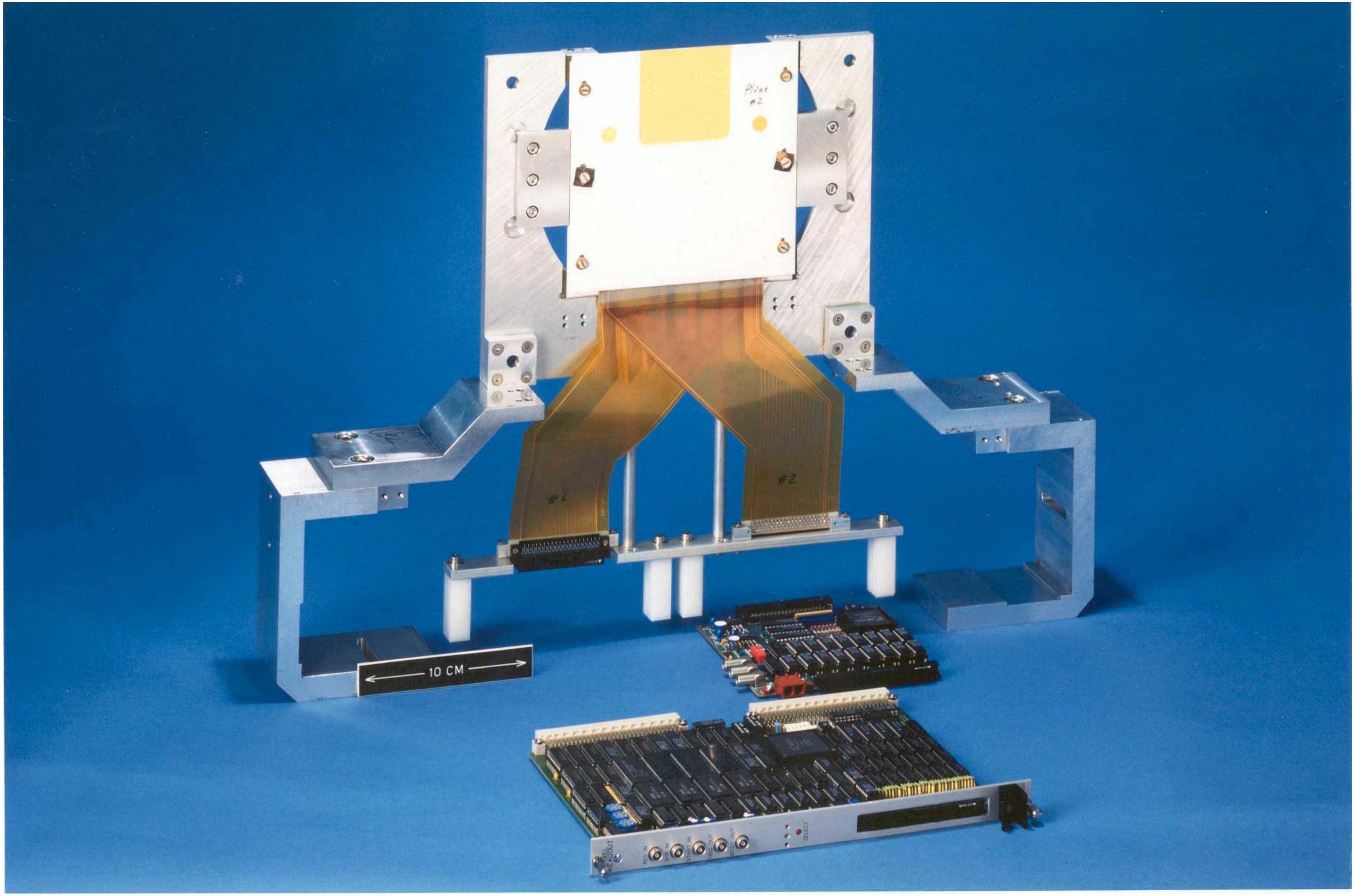
➢ Array:
- 4 ladders mounted on a ceramic

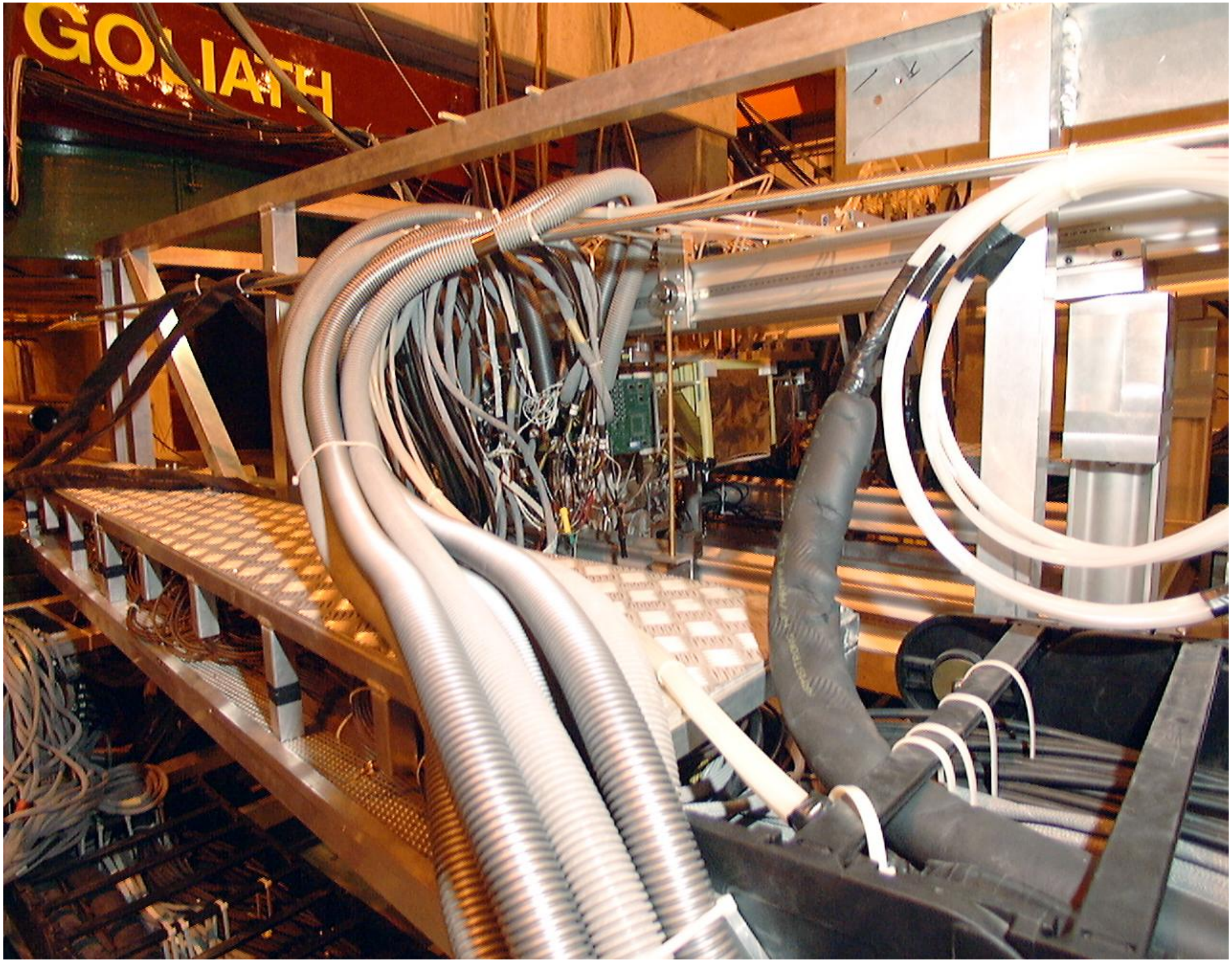
➢ Logical plane:
- 2 arrays mounted face-to-face and staggered by ≈4 mm to cover dead areas
- ≈5x5 cm^2, 8 ladders, ≈98K sensor elements

Silicon Pixel Plane

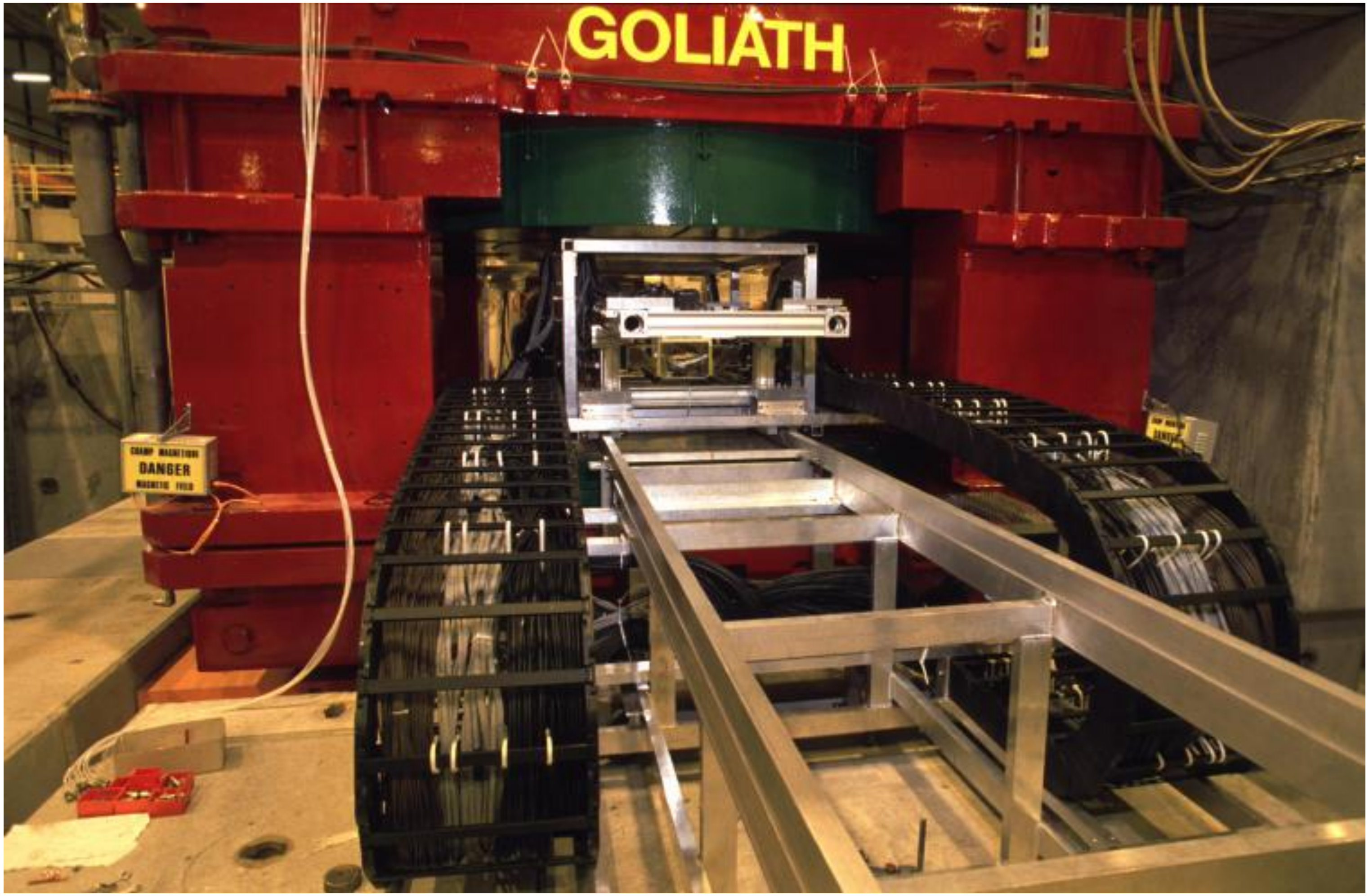
WA97/NA57 Pixel detector with electronics




Plane #2
#1
#2
10 CM
PIXEL READOUT
RES IN
STP IN
START IN
TRIG OUT
BUSY OUT
SELECT


GOLIATH

NA57 Set-up



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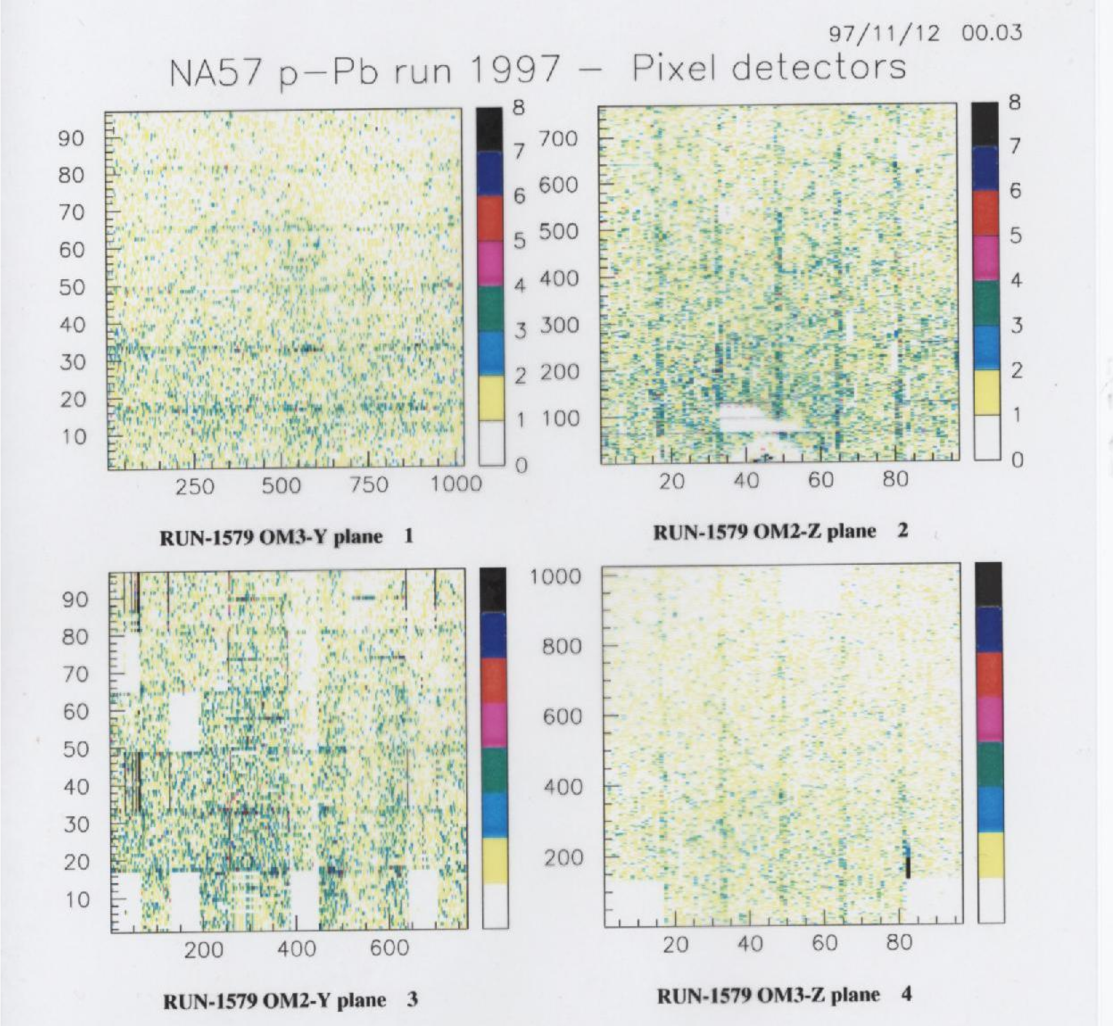
NA57 Hit Maps

- Things do not go always smoothly as one would like!



NA57 Hit Maps

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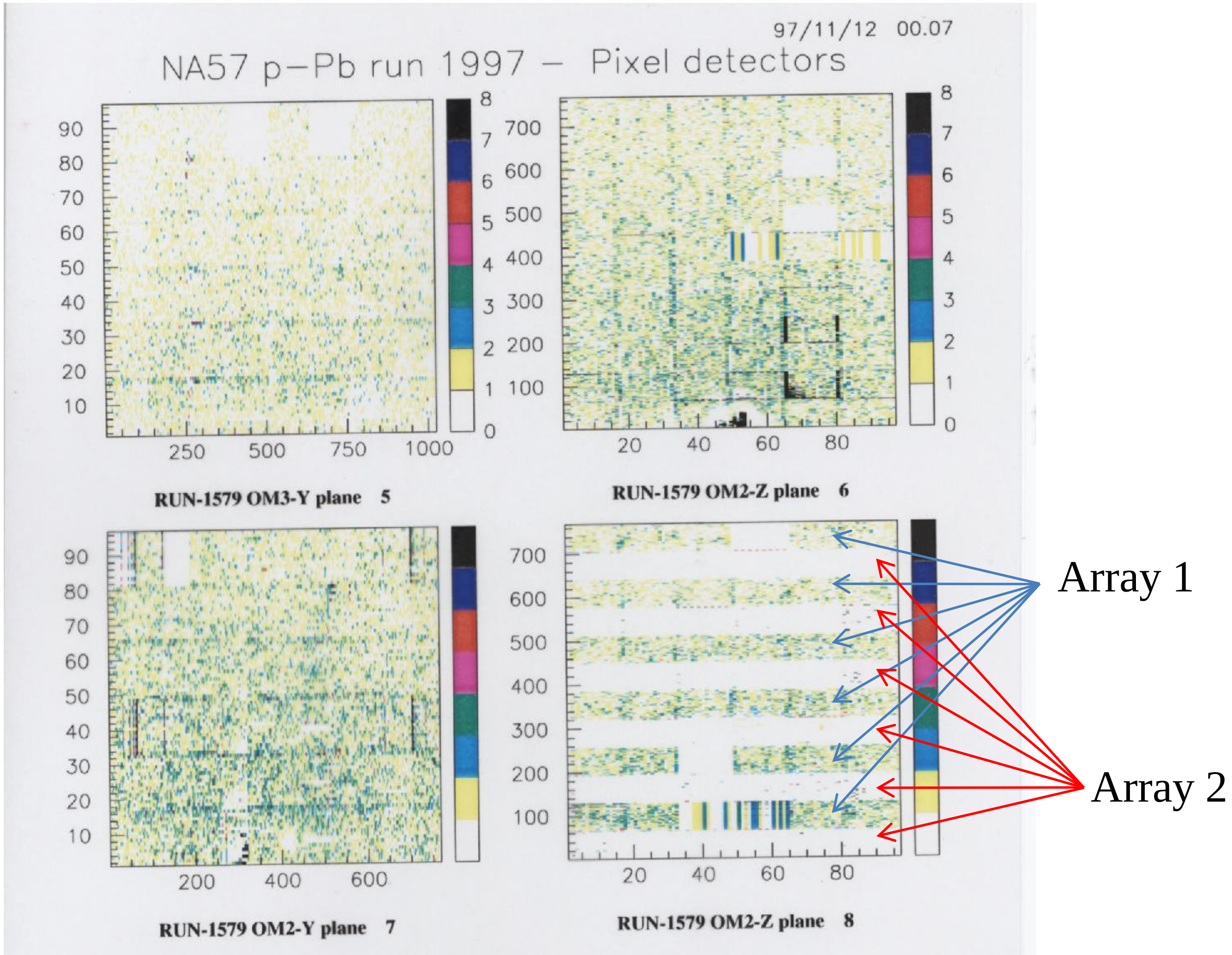
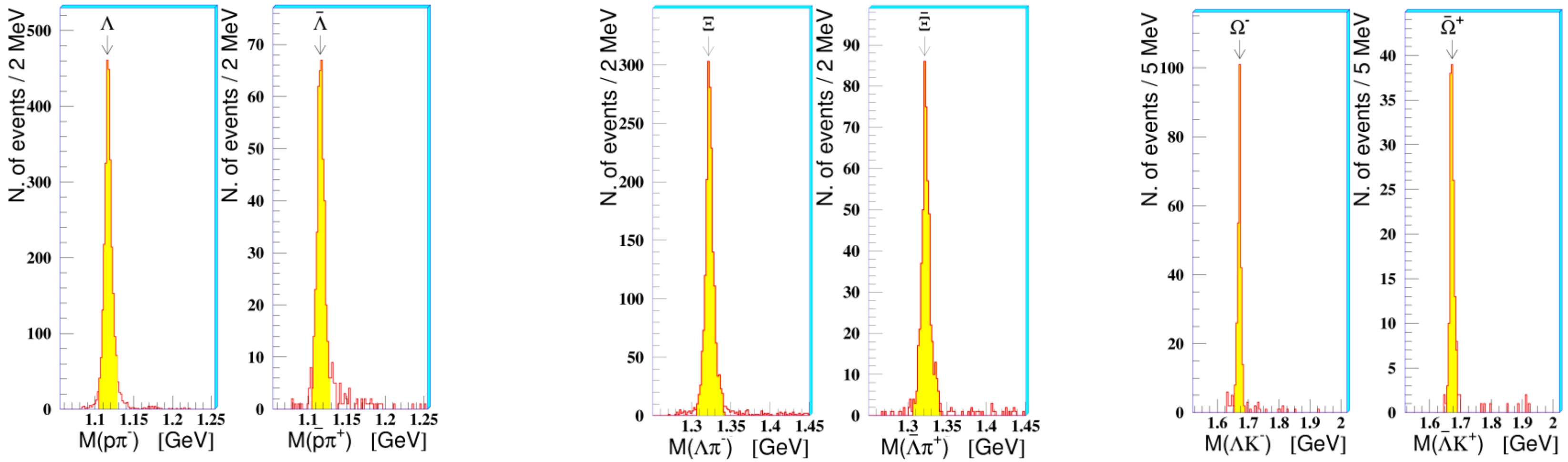


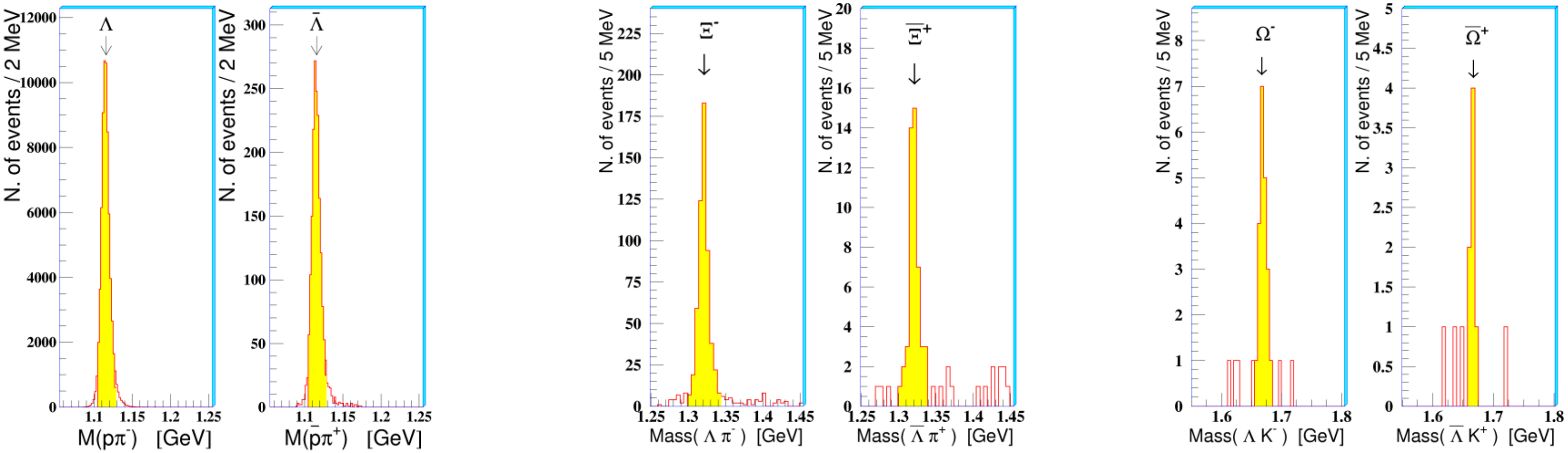
Hyperon signals in NA57

Pb-Pb @ 160 A GeV/c

background unsubtracted

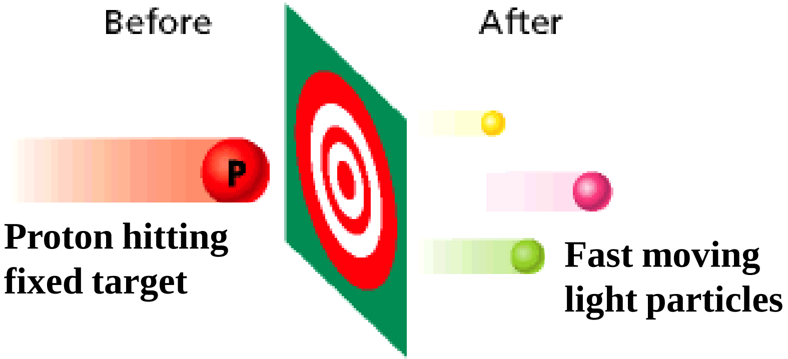


Pb-Pb @ 40 A GeV/c



Fixed Target vs Collider

- Beam incident on stationary target
  - Interaction products have large momentum in forward direction
  - Large “wasted” energy ⇔ small √s
  - Intense beams/large target ⇒ high rate
  - Secondary beams can be made.



$$p_1 = (E_1, \bar{p}_1) \quad p_2 = (E_2, \bar{p}_2) \quad E^2 = p^2 + m_0^2$$

Centre of Mass energy squared $s = E_{cm}^2 = (p_1 + p_2)^2$

$$\Rightarrow E_{cm} = \left[(E_1 + E_2)^2 - (\bar{p}_1 + \bar{p}_2)^2 \right]^{1/2}$$

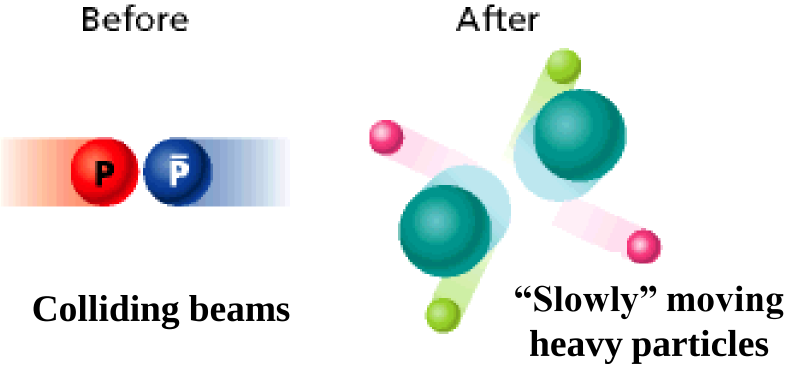
Shooting a particle beam on a “fixed target”:

$$E_{CM} = 2\sqrt{Emc^2} \sim 20 \text{ GeV for } E = 100 \text{ GeV}$$

$m = 1 \text{ GeV}/c^2$

Fixed Target vs Collider

- Head-on colliding beams
  - Incoming momenta cancel
  - $\sqrt{s} = 2E_{beam}$
  - Same magnetic field deflects opposite charges in opposite directions
    - *antiparticle accelerator for free!*
    - particle/antiparticle quantum numbers also cancel



$$\text{Event Rate R} = L\sigma$$

particles per bunch

$$\text{Luminosity} = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

frequency

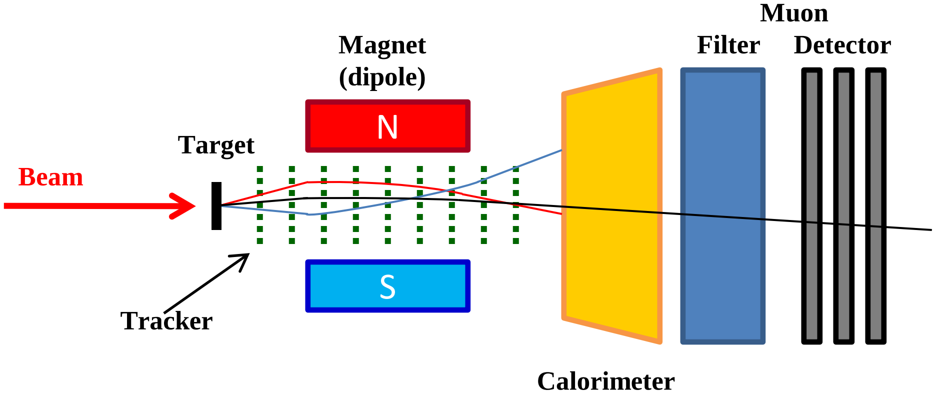
bunch size

Colliding head-on two particle beams:

E_{CM} = 2E ~ 200 GeV for E = 100 GeV

Fixed Target vs Collider

➢ Geometrical layout concept



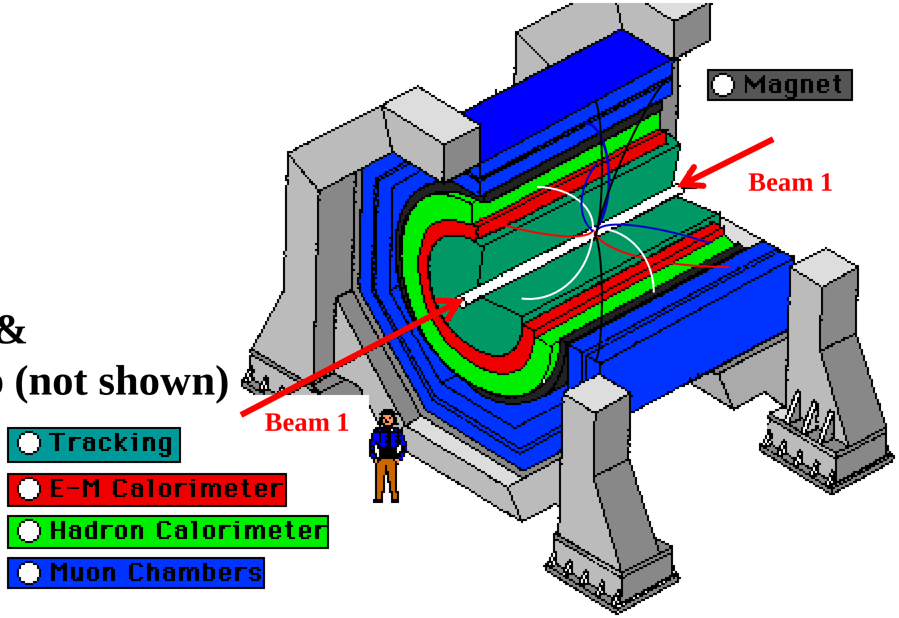
Fixed target

- Magnet spectrometer
- Limited solid angle dΩ coverage
- Relatively easy access (cables, maintenance, etc)

Collider

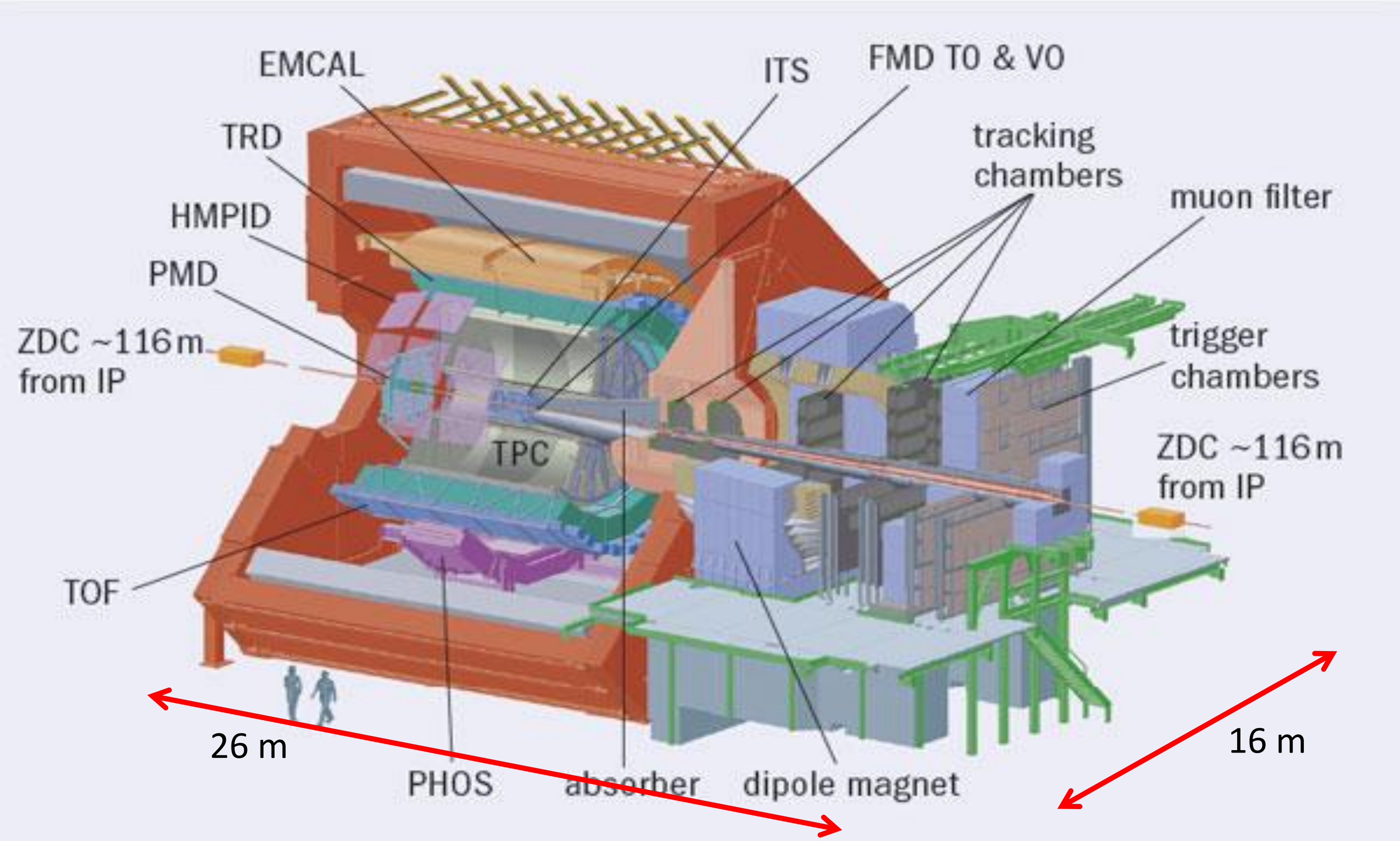
- 4π multipurpose detector
- full dΩ coverage
- limited access

Barrel & Endcap (not shown)



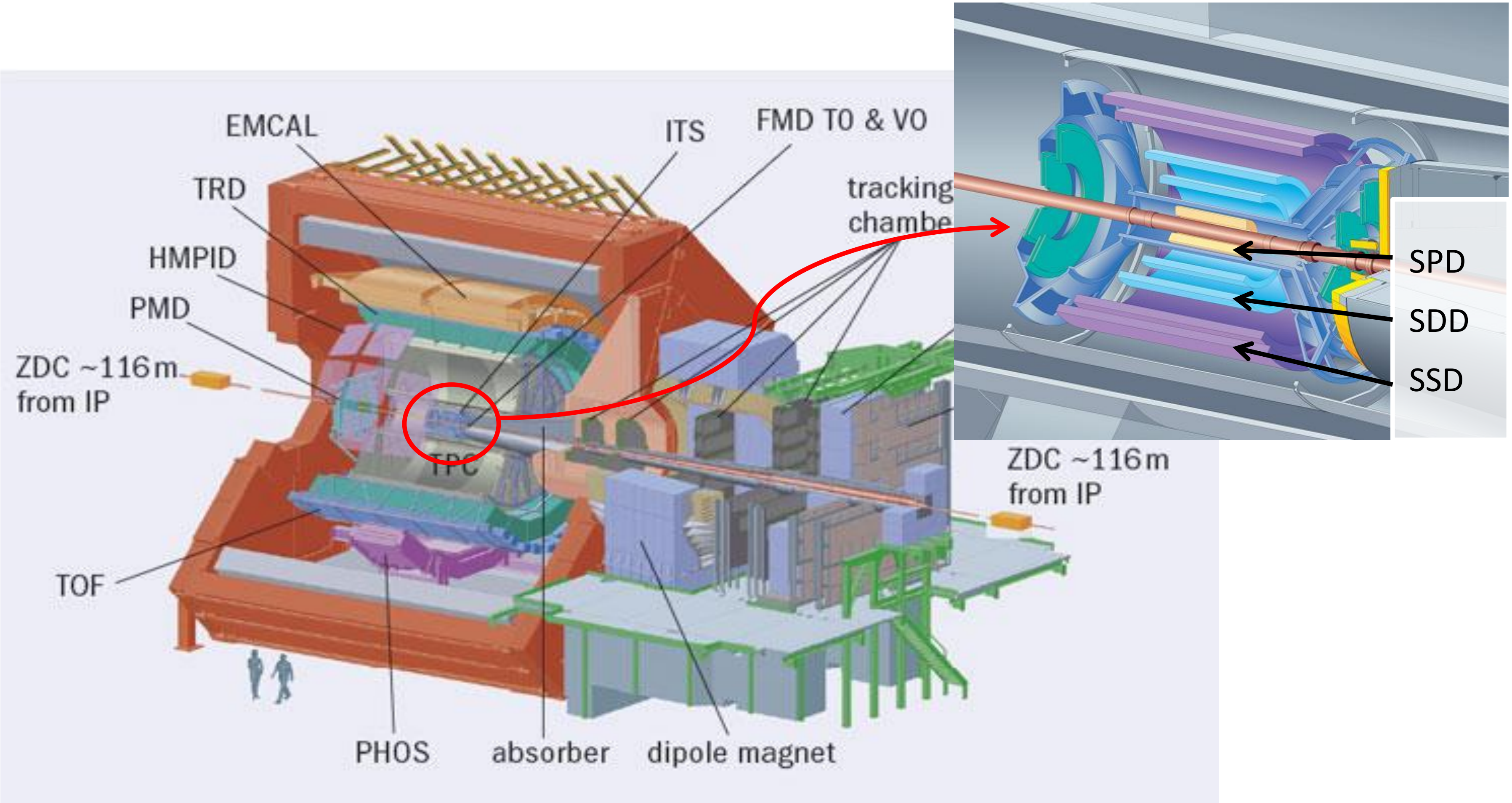
ALICE LHC experiment

- Experiment designed for heavy ion collisions
    - Pb-Pb @ 2.75+2.75 TeV per nucleon
    - nucleus-nucleus collisions: study strongly interacting matter
    - p-p collisions: reference data for heavy ion program, unique physics



ALICE Inner Tracking System

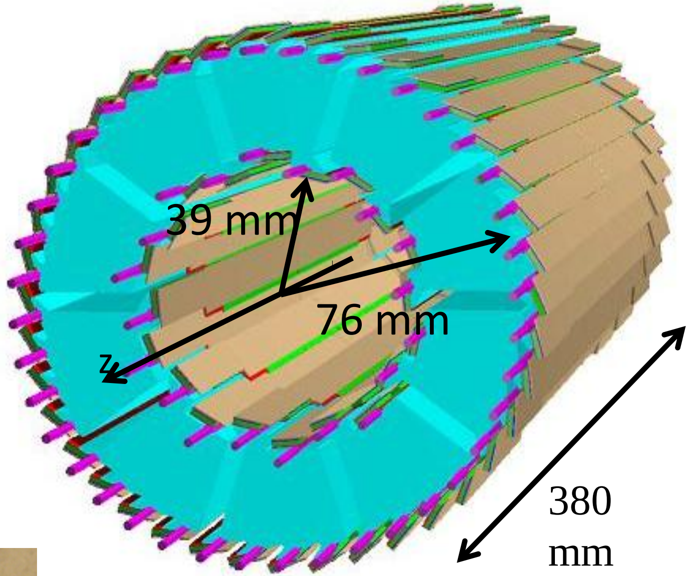
- 3 different silicon detector technologies in 6 barrel layers
  - 2 layers each: Pixels (SPD), Drift (SDD), double side Strips (SSD)



ALICE Silicon Pixel Detector

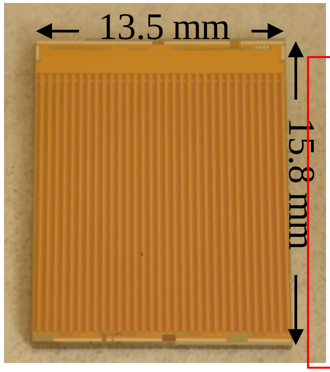
➢ Requirements

- 2D digital readout (256 μs, no ambiguity)
- high efficiency (> 99%)
- high spatial precision
  ~12 μm in the bending plane)
- limited material budget (~1% X_0 per layer)
- fast signal for L0 trigger



➢ Characteristics

- 2 innermost layers, 0.24 m^2
- ~ 9.8 M readout channels
- pixel size 425 x 50 μm^2 (z x rφ)
- sensor thickness 200 μm
- readout chip 0.25 μm CMOS technology
- power consumption ~ 1.35 kW
- internal clock 10 MHz



➢ **ALICELHCb1** readout chip
- mixed signals
- 8192 cells
  256 row x 32 col
- 50x425μm^2

See also lectures:

- *Hybrid Silicon Pixel Detectors* - ***M. Keil***
- *Present and Future pixel systems at the LHC* - ***D. Dobos***

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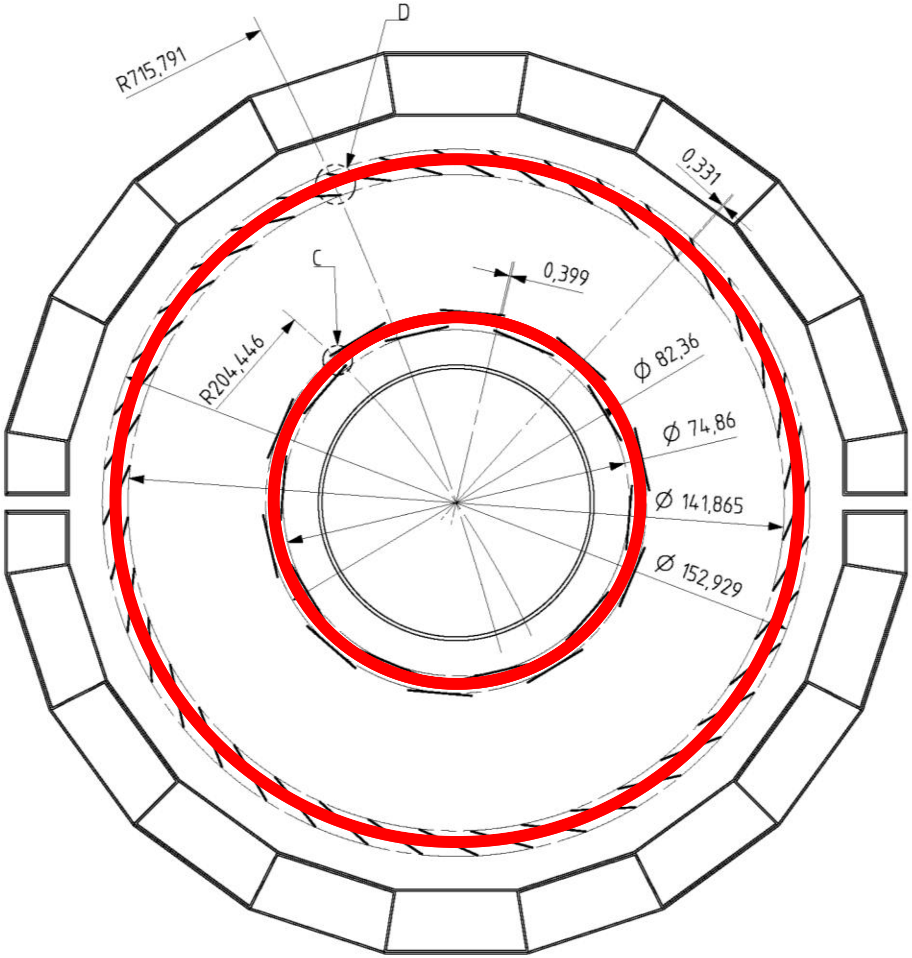
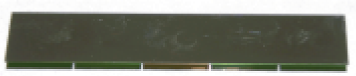
“Hermetic” 2-layer barrel

“Hermetic” ⟺ designed to let escape as few particles as possible



SPD segmentation



ladder

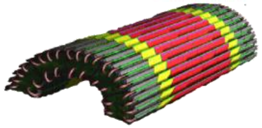
- 5 read-out chip
- 1 sensor

Half-stave

- 1 multilayer bus
- 1 MCM
- 2 bump bonded ladders

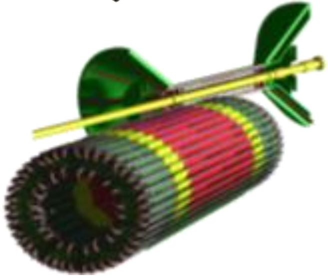
Sector

- 12 half-staves



Half-barrel

- 5 sectors



SPD

- 2 half-barrels

Total SPD Components

☐ 1200 read-out chips
☐ 240 sensors

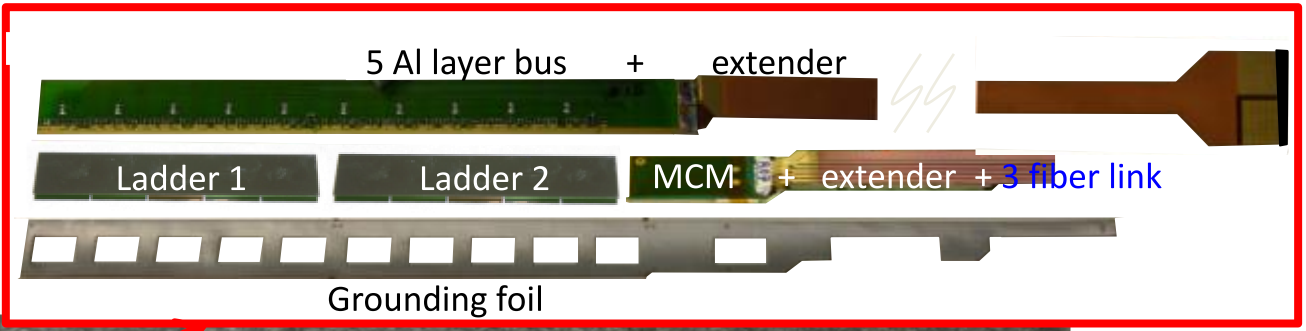
☐ 120 multilayer buses
☐ 120 MCMs
☐ 240 ladders

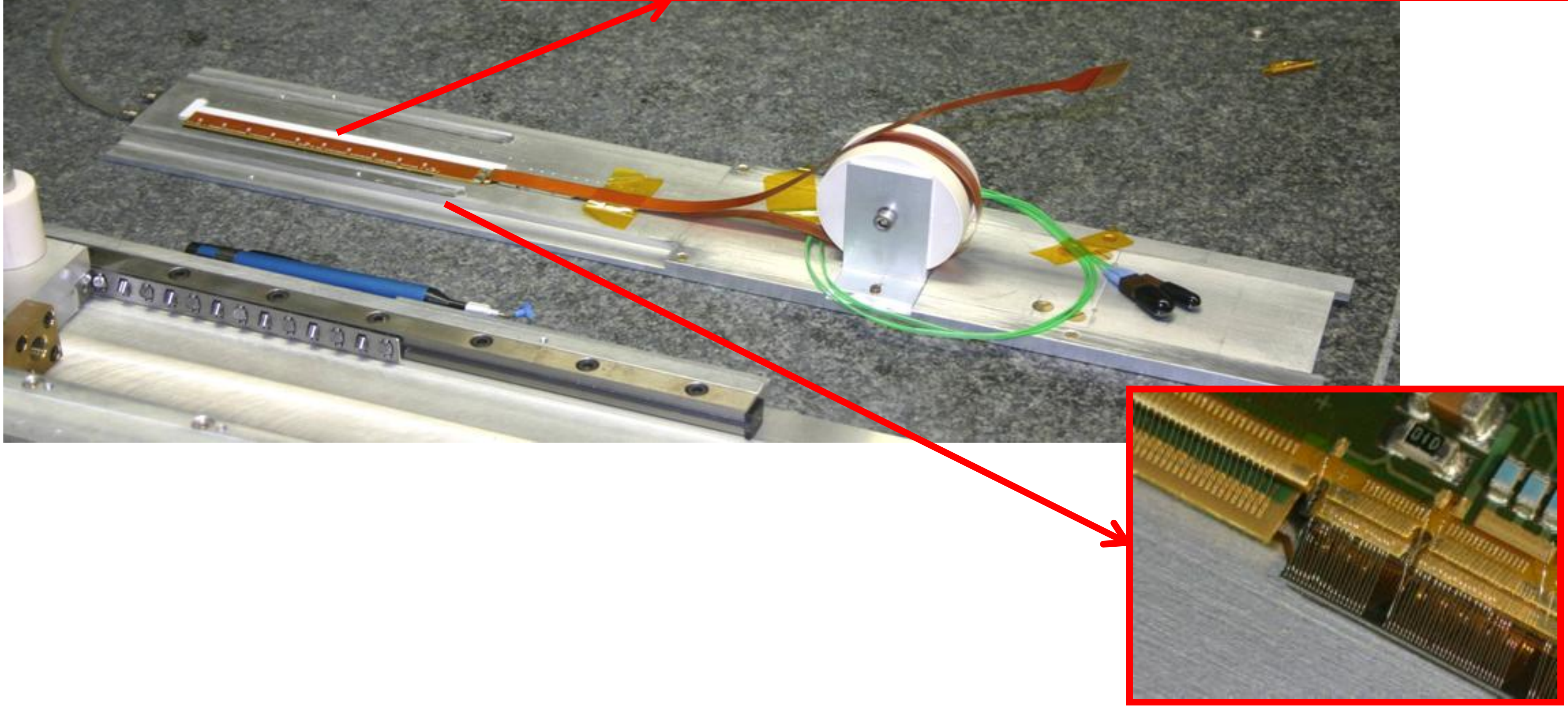
☐ 120 half-staves

☐ 10 sectors

☐ 2 half-barrels

SPD Half-stave

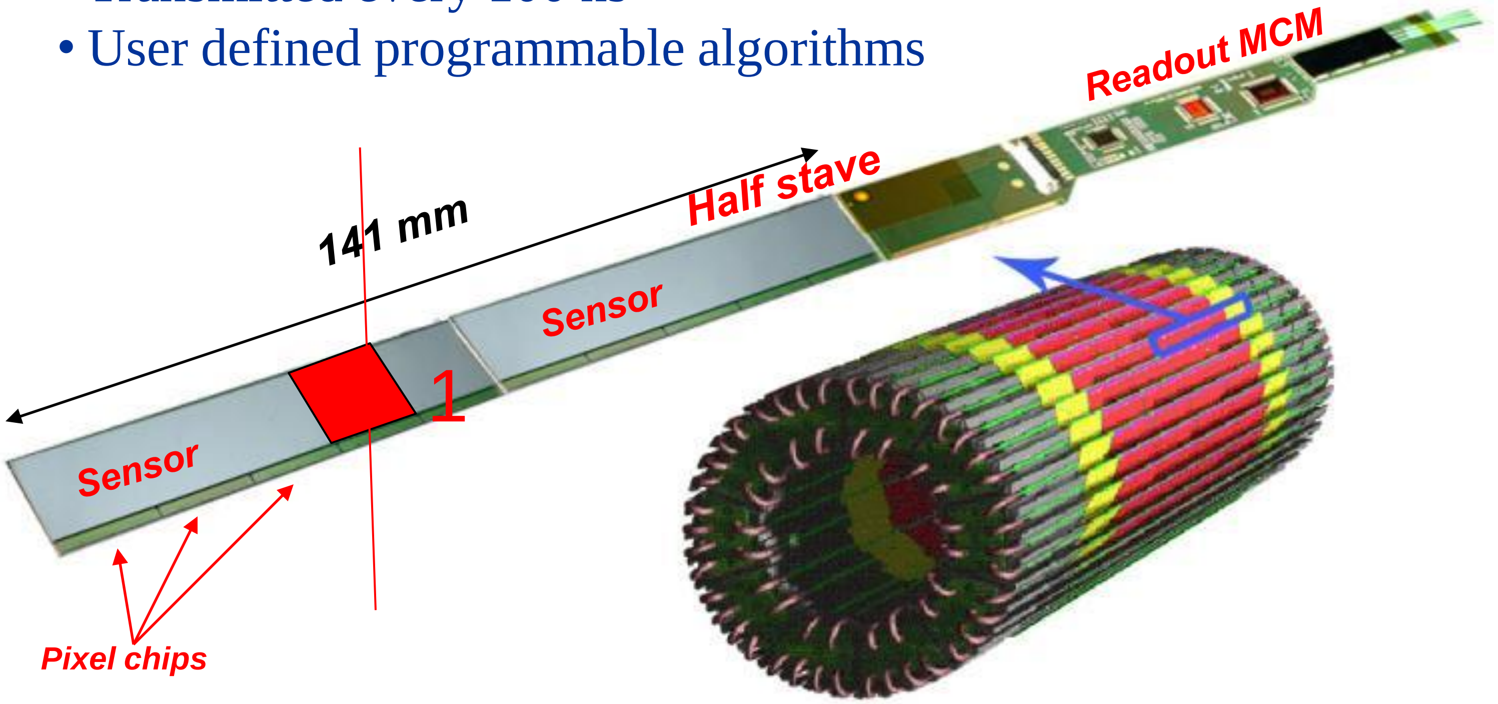




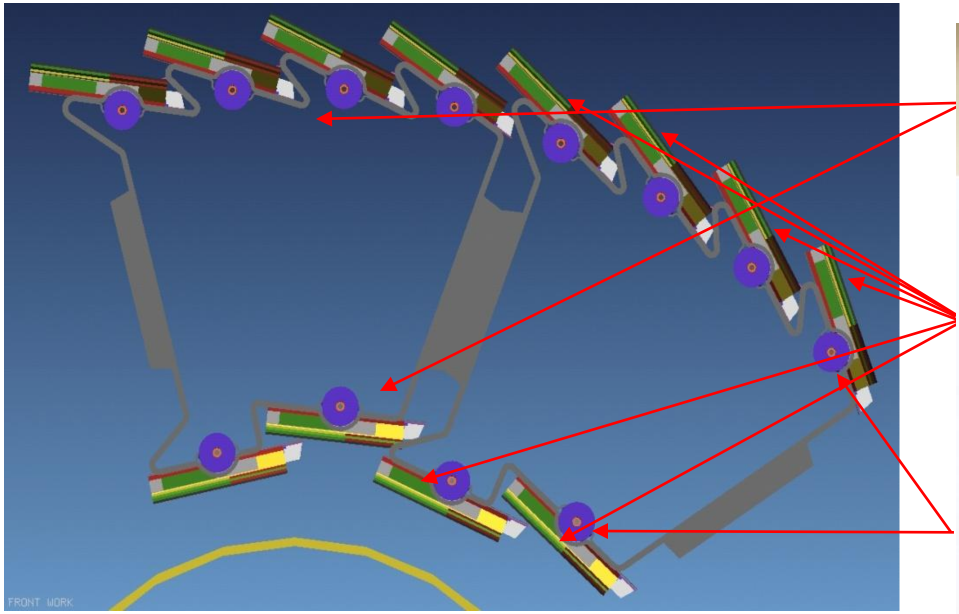
Inner surface: 40 half-staves

Prompt Pixel Trigger

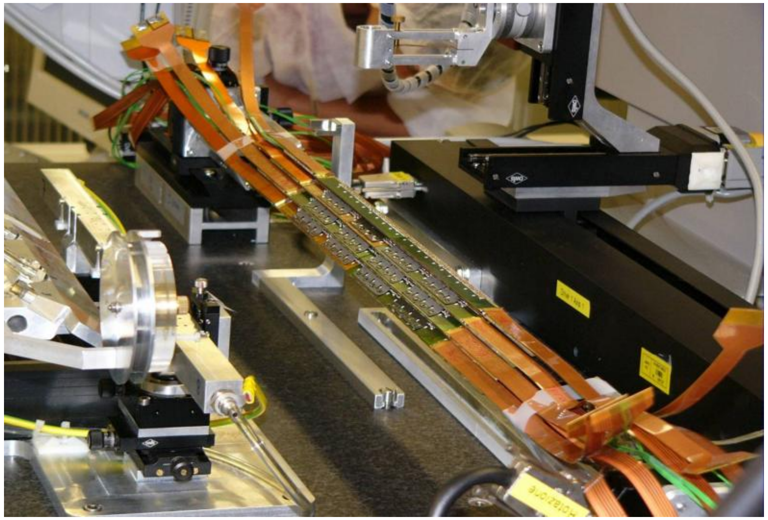
- **Unique L0 trigger capability**
  - 120 SPD modules (half-staves), each contains 10 readout pixel chips
  - Prompt trigger signal (Fast-OR) from each chip
    - Active if at least one pixel hit in the chip matrix
  - 10 bits from each 120 modules → Extract and *synchronize* 1200 FastOR signals
    - Transmitted every 100 ns
    - User defined programmable algorithms



SPD layout



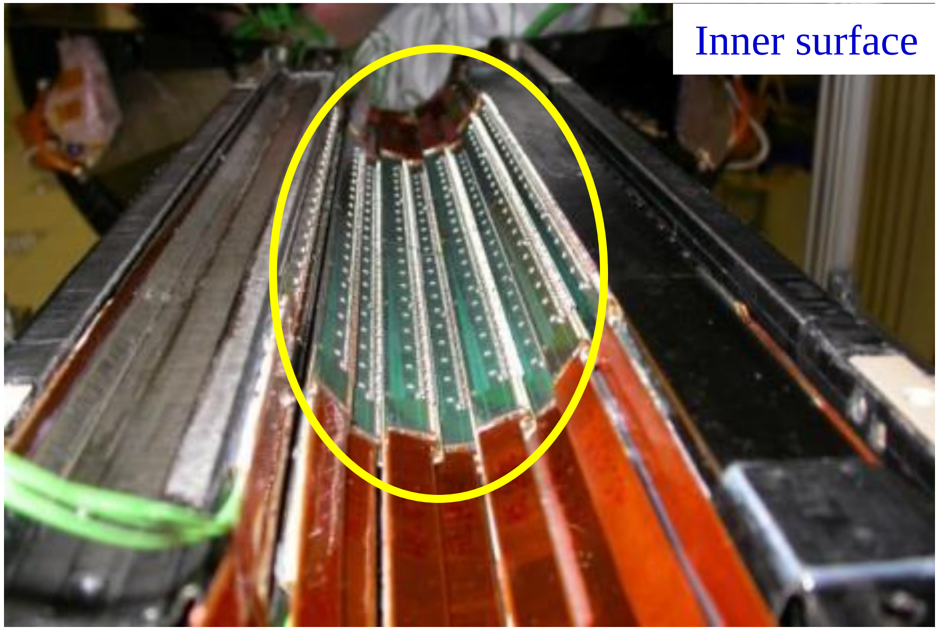

Carbon Fiber Support Sector (CFSS)



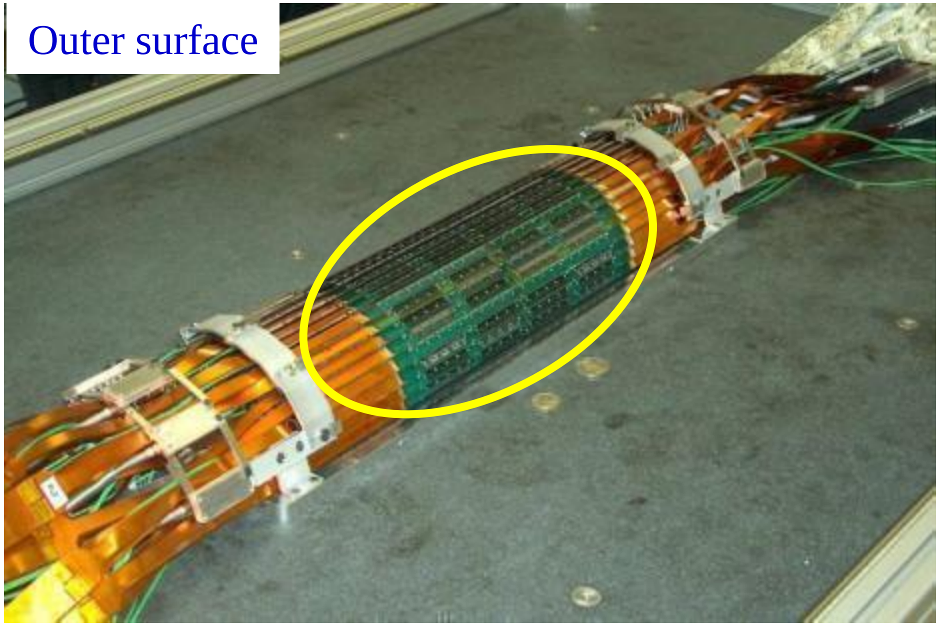
SPD pre-commissioning

SPD assembly

- 5 Sectors mounted together side to side make one Half-barrel



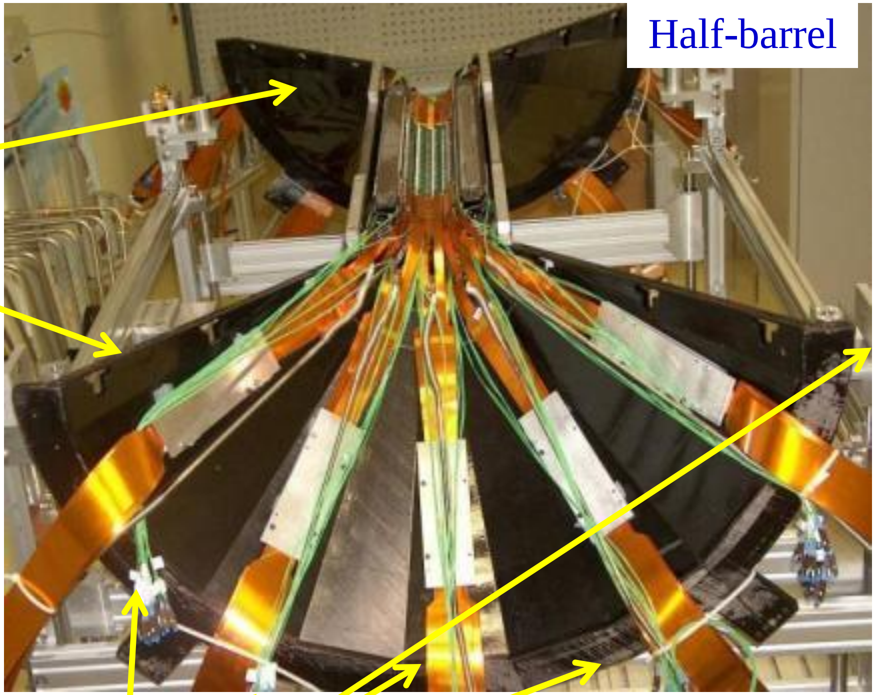
Inner surface



Outer surface

SPD assembly

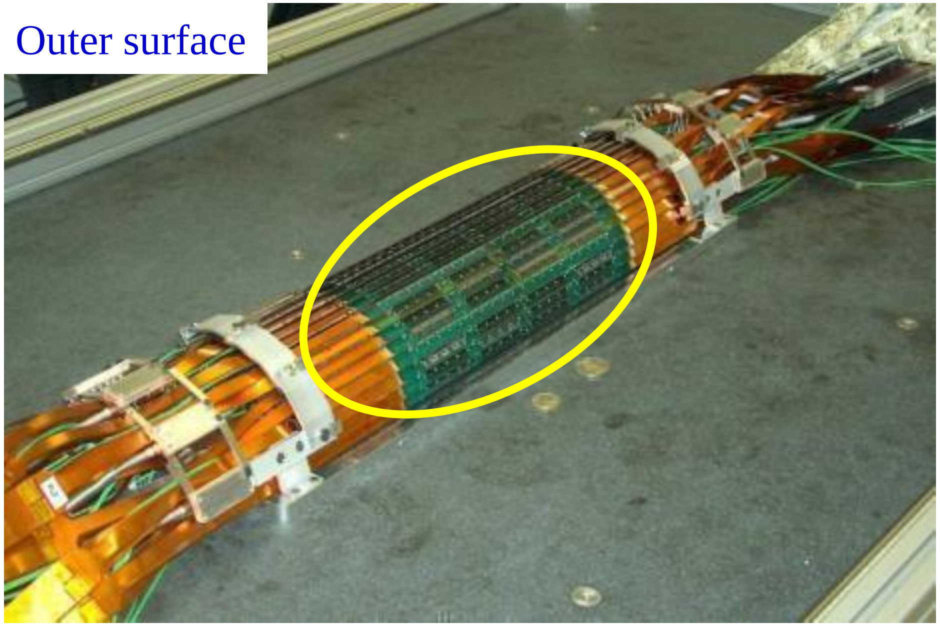
- 5 Sectors mounted together side to side make one Half-barrel



Half-barrel

Half-cones

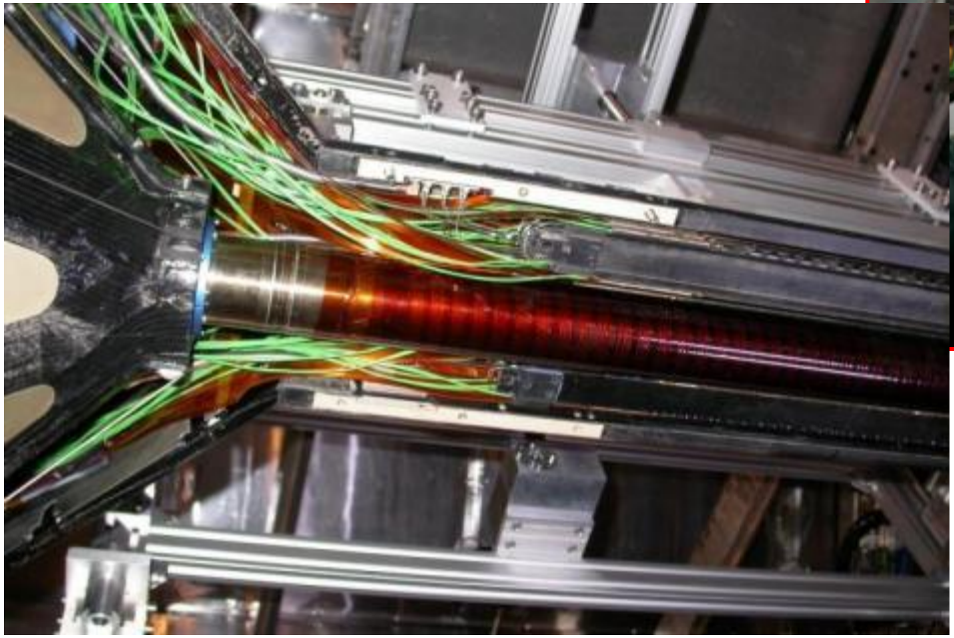
Services: flat cables, cooling ducts, optical fibers

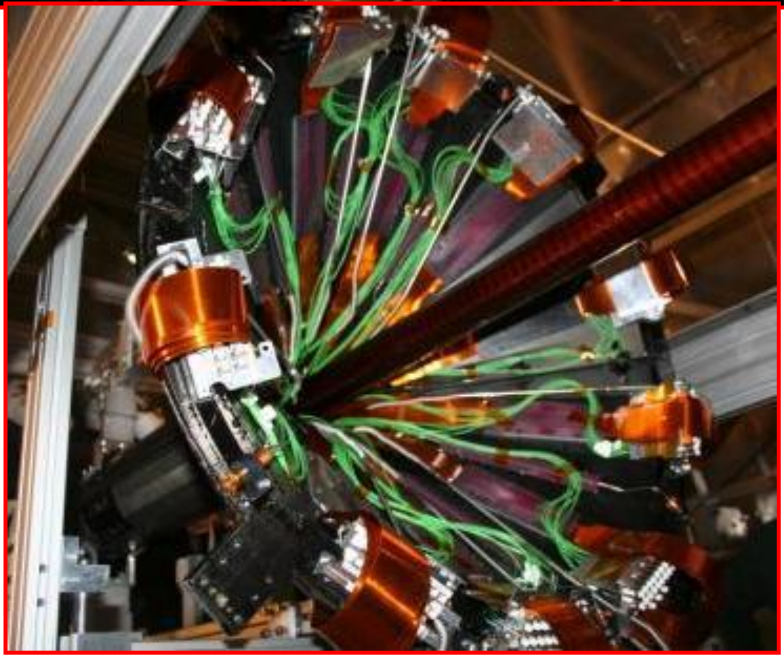


Outer surface

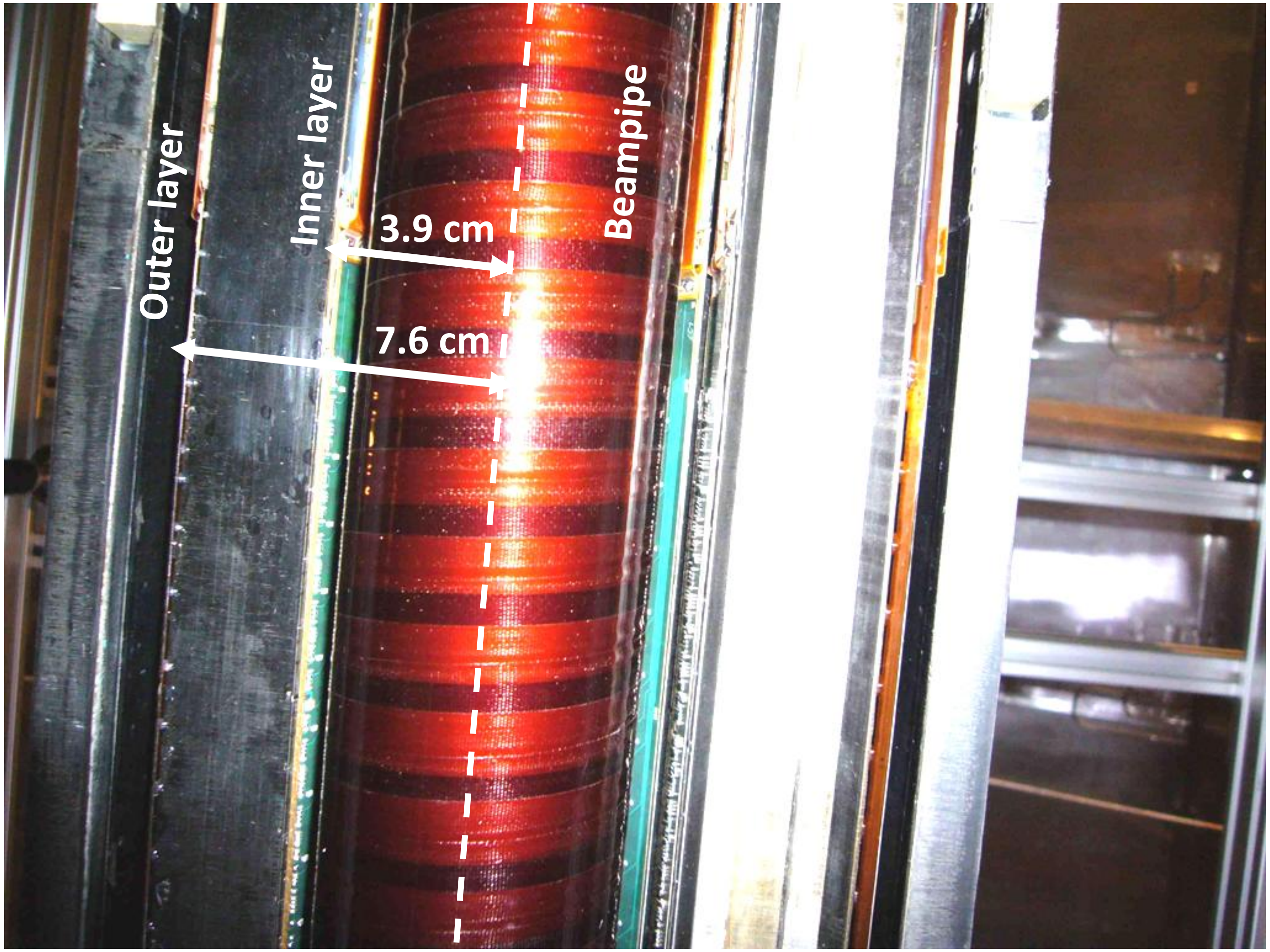
SPD installation

- ➢ SPD installed in ALICE in Jun‘07





- ➢ SPD Internal mean radius ≈ 39 mm
- ➢ Beam pipe radius ≈ 30 mm
- ➢ Minimum distance inner layer to beam-pipe ≈ 5 mm



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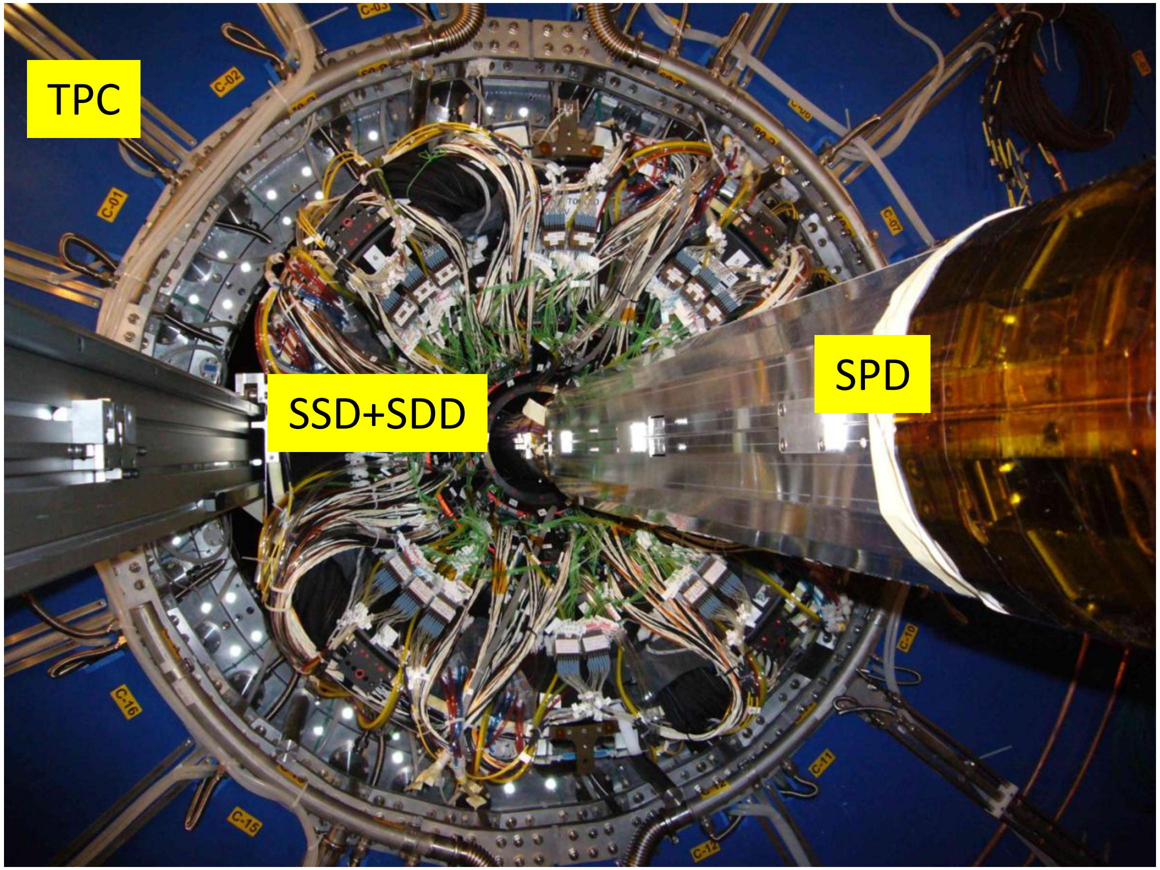
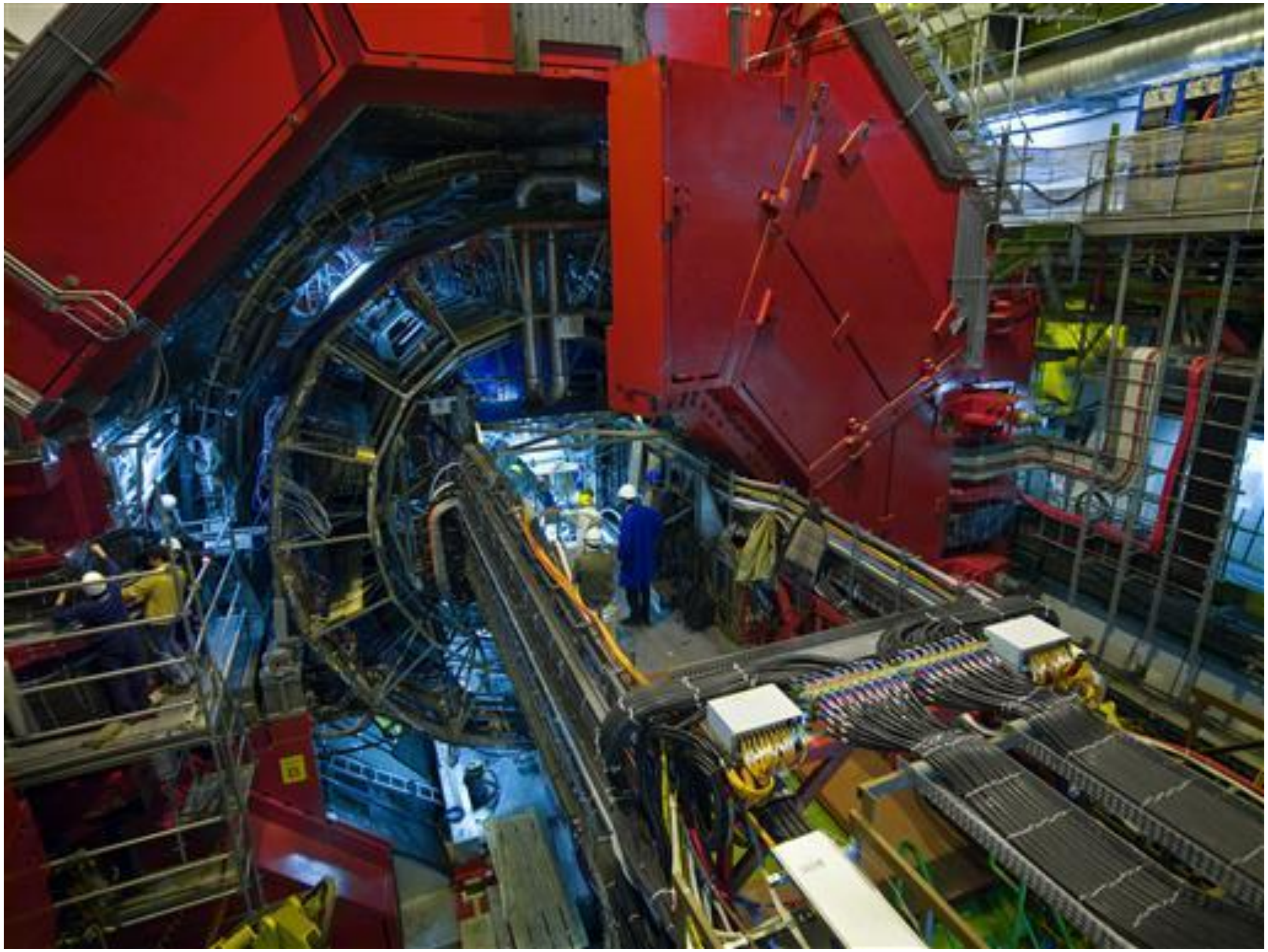
"Russian Doll" Installation

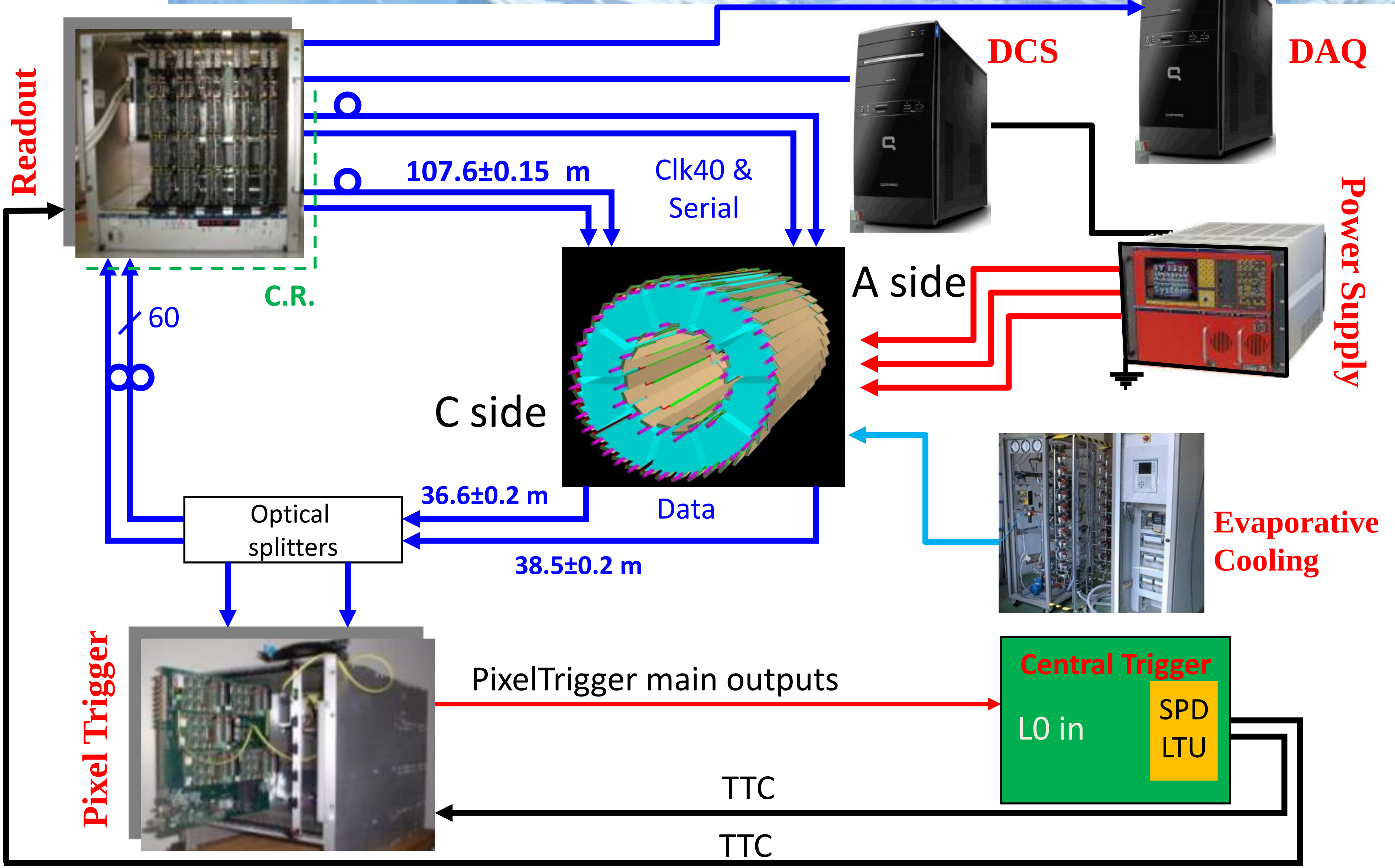
- "Russian doll" installation scheme



ALICE



SPD System



Readout

C.R.

60

107.6±0.15 m

Clk40 & Serial

DCS

DAQ

A side

C side

Power Supply

36.6±0.2 m

Data

38.5±0.2 m

Optical splitters

Evaporative Cooling

Pixel Trigger

PixelTrigger main outputs

Central Trigger

L0 in

SPD LTU

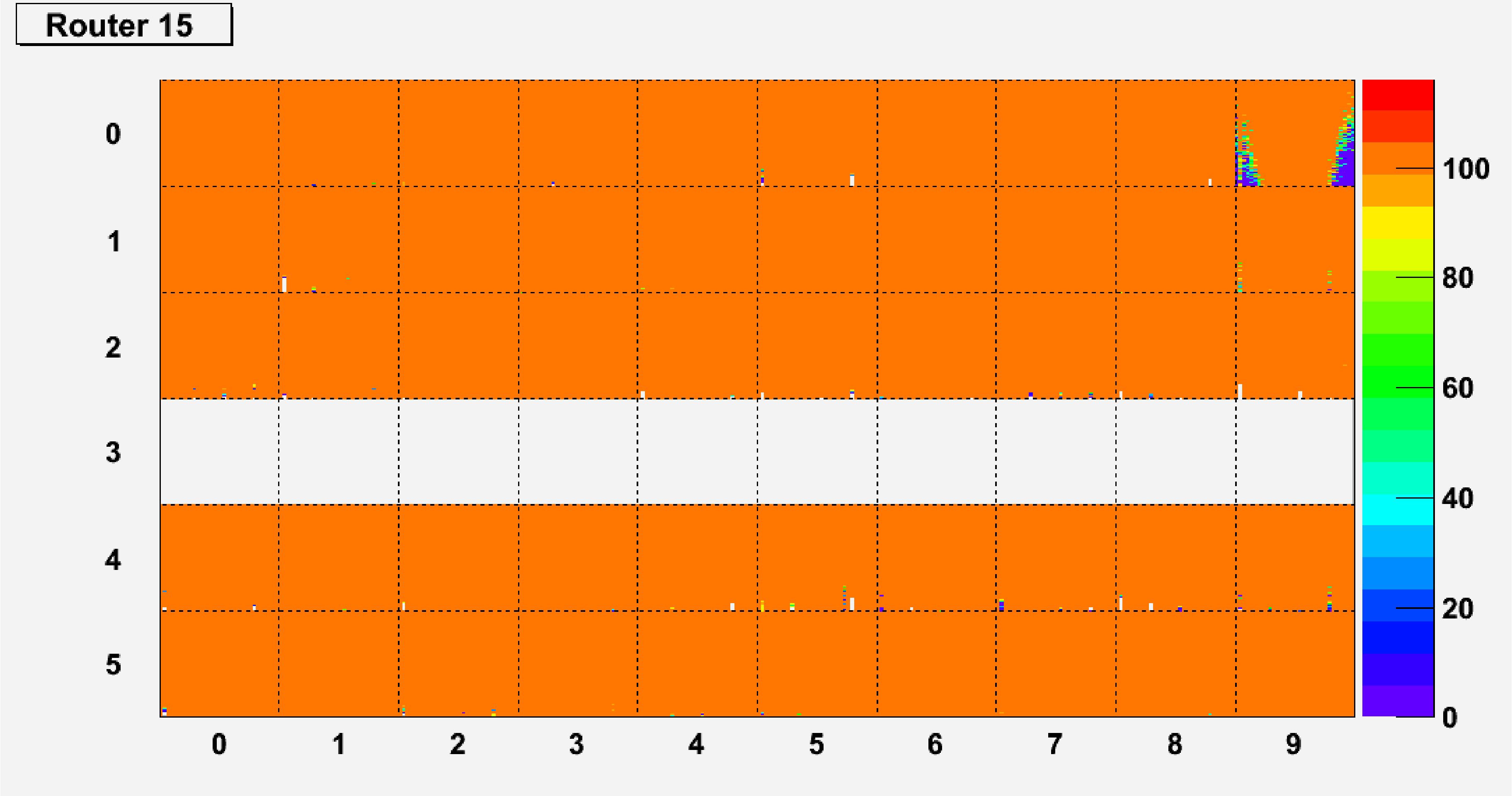
TTC

TTC

SPD Commissioning

- And again....

  Things do not go always smoothly as one would like!



SPD Commissioning

- And again….

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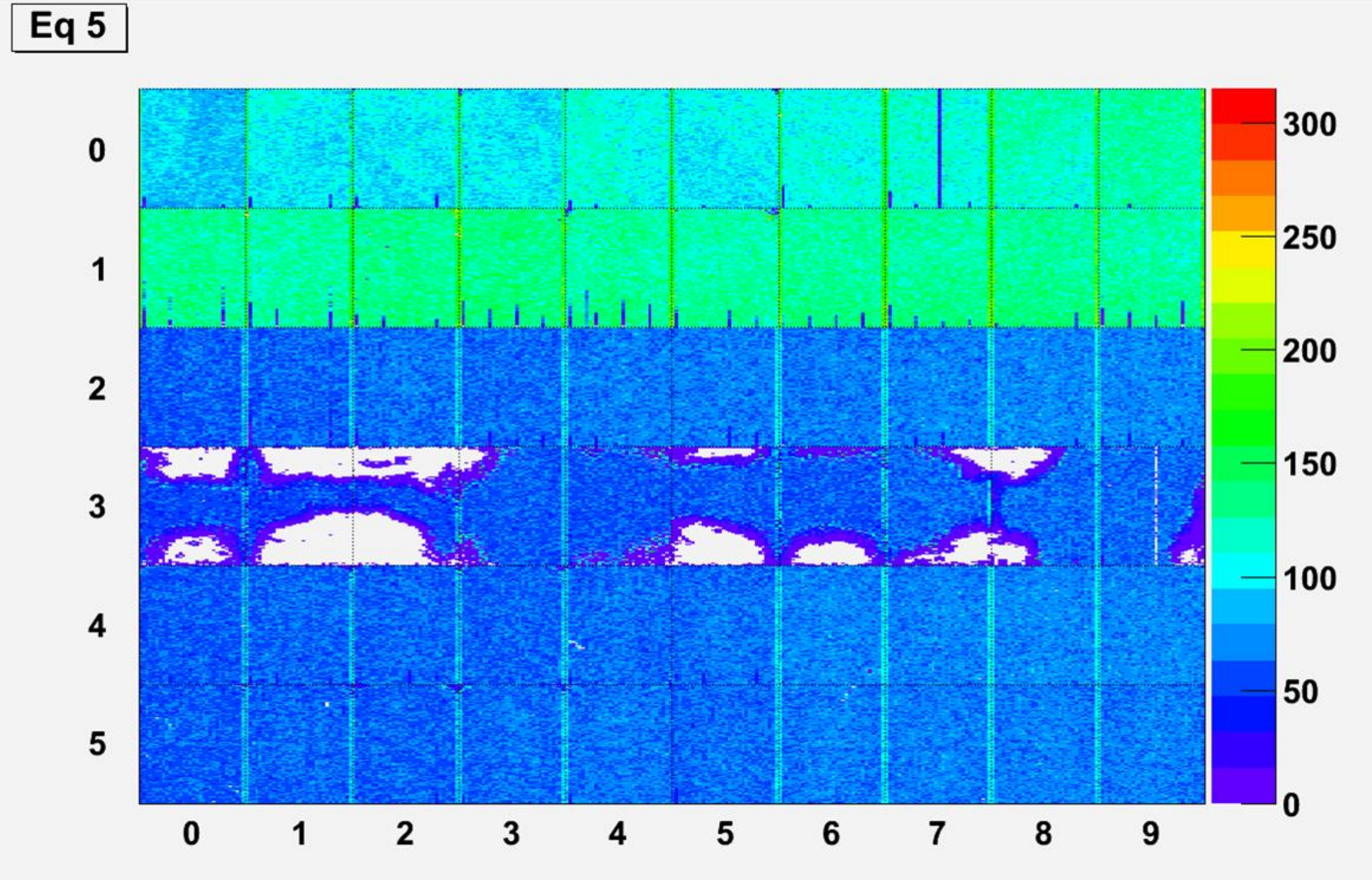
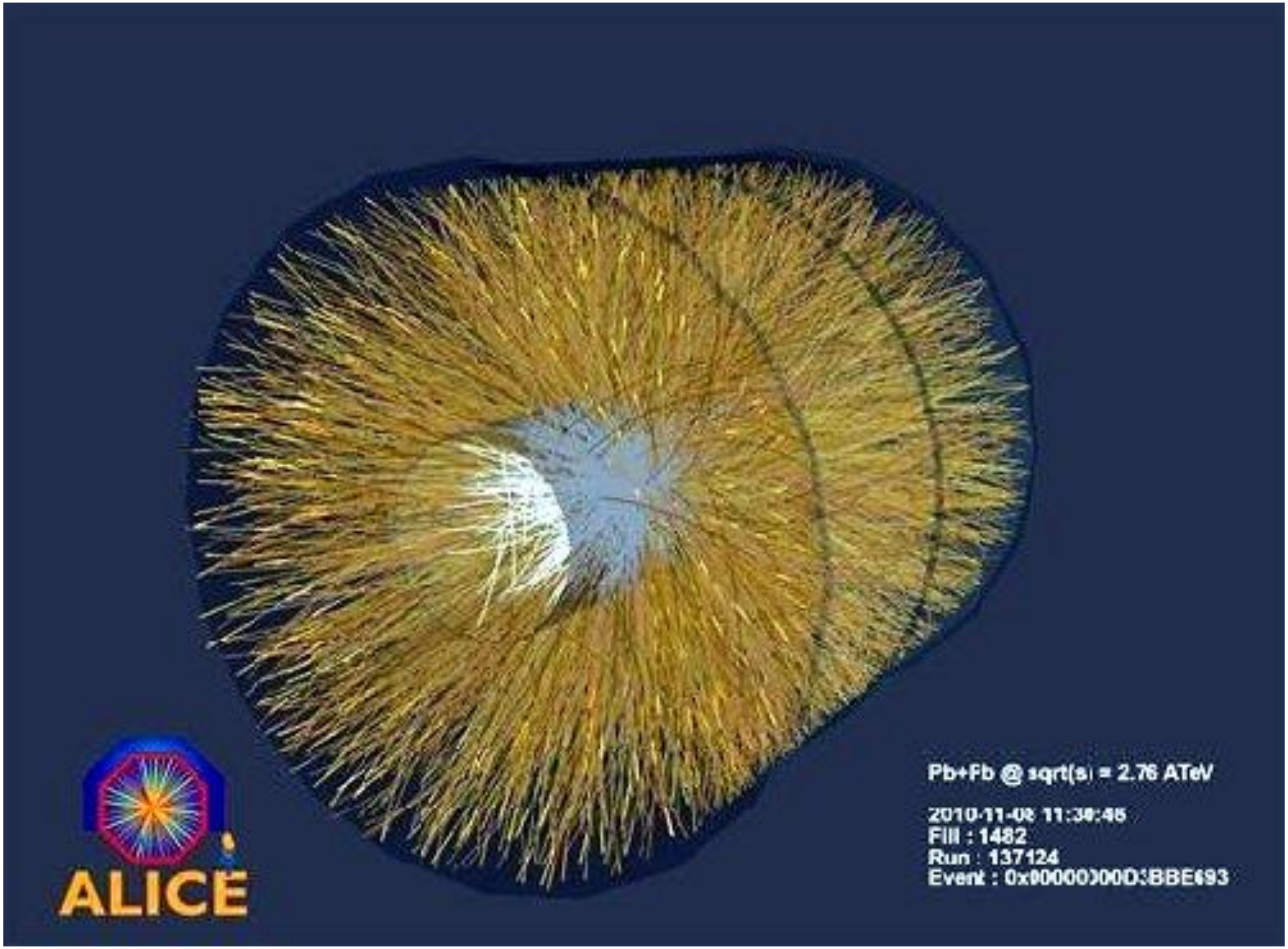


ALICE Pb-Pb event



The lesson learnt so far….

- We have developed and built a highly performing and robust vertex detectors for the ALICE experiments:
  - Performance well in agreement with the design specs and goals
  - It can survive also to "unforeseen treatments"
  - First physics results published shortly after the data taking

We can be proud of all that!!!

however, services and accessibility may be improved

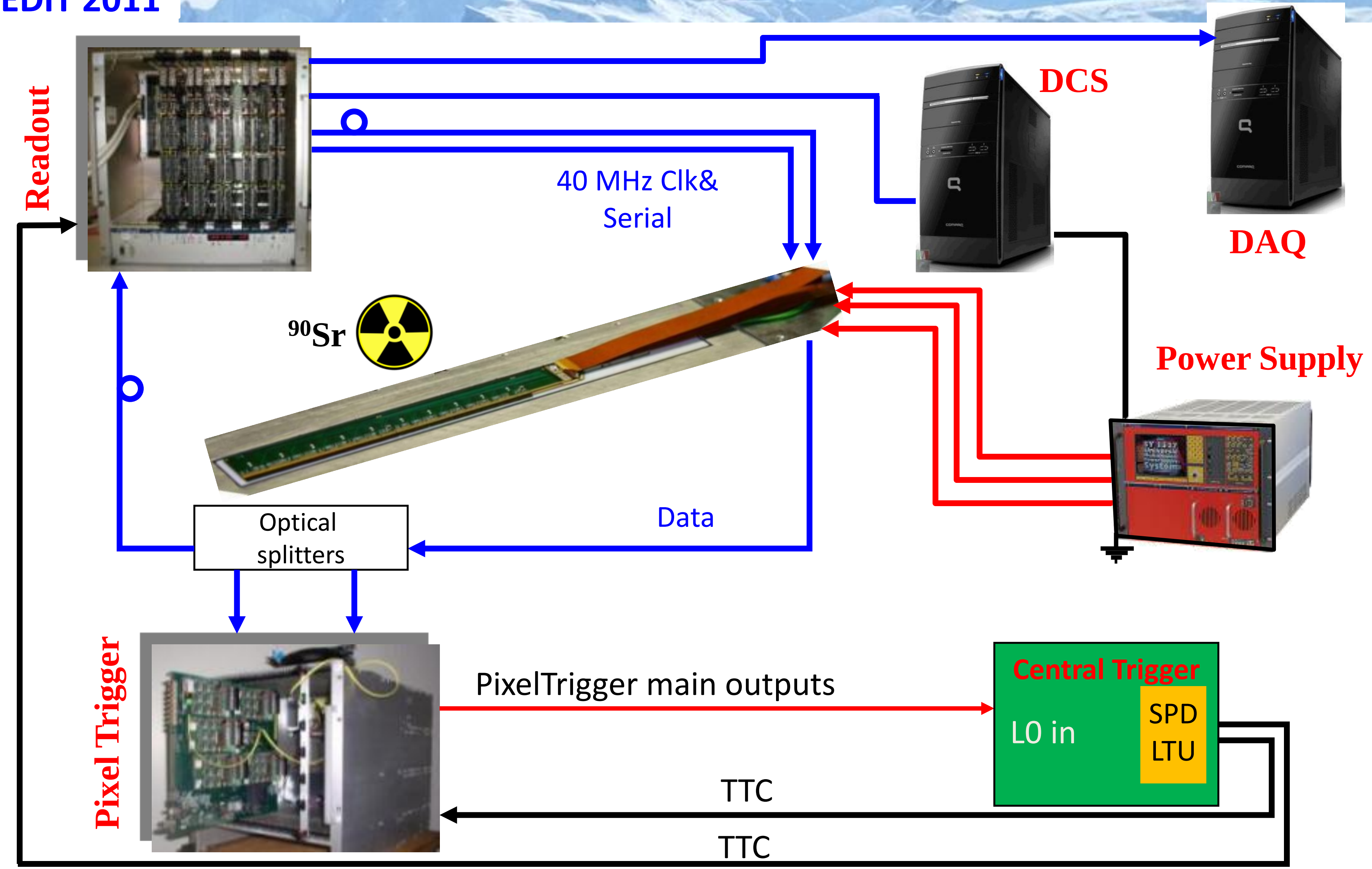
- Optical connections require
- Power Supply System
- Cooling system

Improvements and Optimization ongoing

Conclusions

- Pixel detectors are suitable for tracking in HEP experiments, both fixed target and collider, even in very high multiplicity environment
- At present the innermost layers of almost all experiments are based on pixel detectors
- Designing a pixel tracking detector:
  - Estimate momentum and impact parameter resolution
    - different contributions, not only space point resolution
    - track finding and reconstruction methods

SPD Hands-on



Readout

DCS

DAQ

40 MHz Clk&
Serial

^{90}Sr

Power Supply

Optical
splitters

Data

Pixel Trigger

PixelTrigger main outputs

Central Trigger

L0 in

SPD
LTU

TTC

TTC

Extra Slides

Design a Tracking Detector

- Projecting and Designing a detector is exciting
  - a process lasting years
- Before starting, given an accelerator, ask yourself:
  - What do we want to measure? → signatures
  - How can we measure them? → detectors

Tracking Detector Design

- An ideal detector should provide:
  - Coverage of the full solid angle
  - Measurement of momentum and/or energy
  - Detect, track and identify all particles (mass and charge)
  - Fast response, no dead time

☞ Most of the game is simply not known and therefore your detectors must be designed to be able of facing surprises

- A silicon tracking detector in HEP experiments is an array of several sensitive layers each providing an accurate measurement of space points of the traversing particles to allow:
  - Vertex location
  - Decay lengths
  - Impact parameters

Tracking

- The tracking detectors are pratically always combined with magnetic field in order to measure the particle momenta **p**.

  - Detector space point accuracy can depend on the magnetic field → Lorentz angle

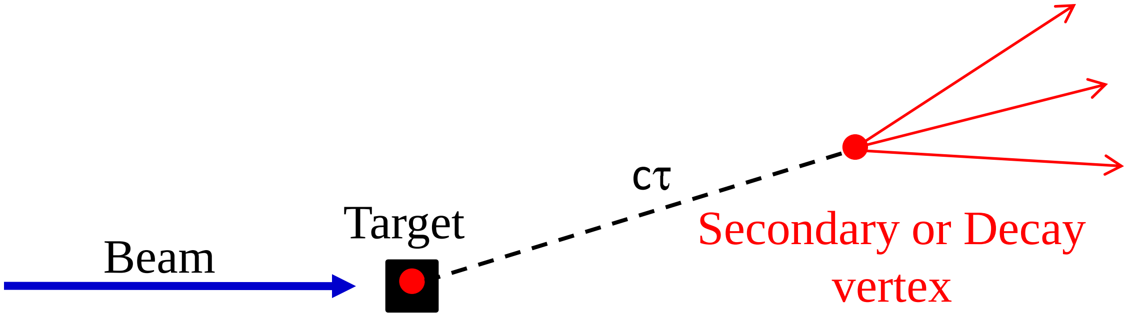
  - Momentum precision can depend on:
    - detector space point accuracy
    - multiple scattering
    - energy loss fluctuations

Tracking precision

- Knowing the decay lenght, i.e. the distance travelled by the particle before it decays, and the momentum, the lifetime of the particles can be determined.

- Let us focus on “long lived particles”,

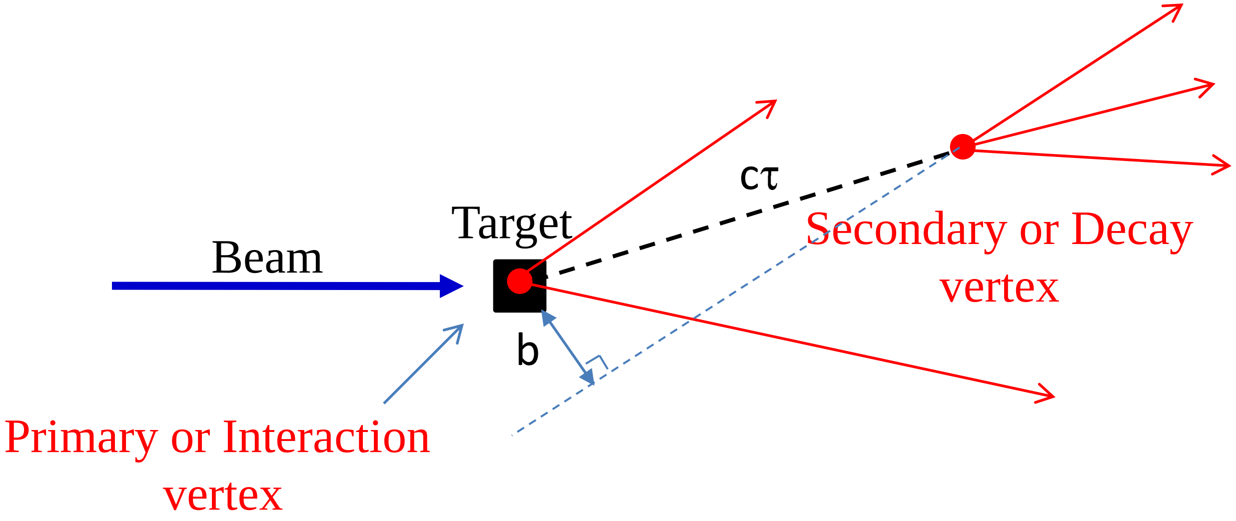
i.e. decay lenght ct ~ cm’s



Primary or Interaction vertex

Tracking precision

- The tracking detector should allow to determine the position of both primary and seconday vertecies with good accuracy.
- Impact parameter b = distance of closest approach of a reconstructed to the true primary vertex



Tracking precision

- The error on the impact parameter depends on:
  - number and distance from the main vertex of the tracking layers as well as the intrinsic precision of each layer, A
  - uncertainty due to multiple scattering in the detector layers and in case in the beam pipe, B
  - detector alignment and stability, C

$$\sigma_b = A^2 + \left(\frac{B}{p} \right)^2 + C^2$$

Momentum precision

- Relative momentum error $\delta p/p$ contributions
  - **space point accuracy:**
    - measurement error σ, momentum itself p and $1/BL^2$

$$\delta p/p \propto \sigma p/BL^2$$

  - **multiple scattering:**
    - square root of material thickness X and 1/BL, and independent on momentum p

$$\delta p/p \propto (\sqrt{X/X_0})/BL$$

  - **fluctuations in ionization losses:**
    - thickness X and 1/p, and independent on B

$$\delta p/p \propto X/p \qquad \text{(empirical approximation)}$$

Detector requirements

- Where to measure the track, i.e. where to place the tracking detector along the path of the track? In other words, what is the optimal material and detector distribution?

  - No material in the central region to minimize the multiple scattering contribution to the momentum precision
  - Detector grouping improves the track finding, in particular at the end of the tracking volume
  - Measurements of the track position in the middle is required for momentum precision

Detector requirements

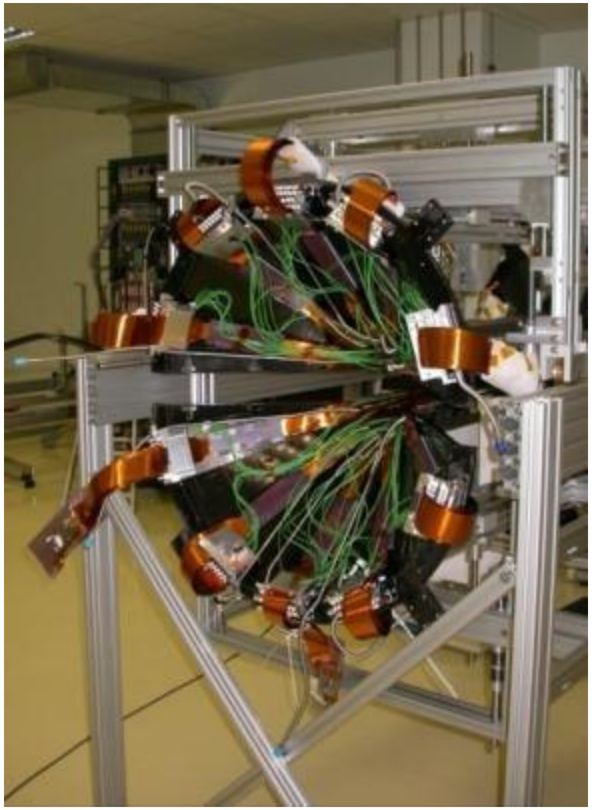
- Requirements for best measurement
  - as close as possible to interaction point
  - maximum lever arm $d_M - d_m$
  - maximum number of space points
  - high spatial resolution
  - smallest amount of material between interaction point and 1st layer
  - good stability and alignment – continuously measured and correct for
  - 100% detection efficiency
  - fast readout to reduce pile up in high flux environments

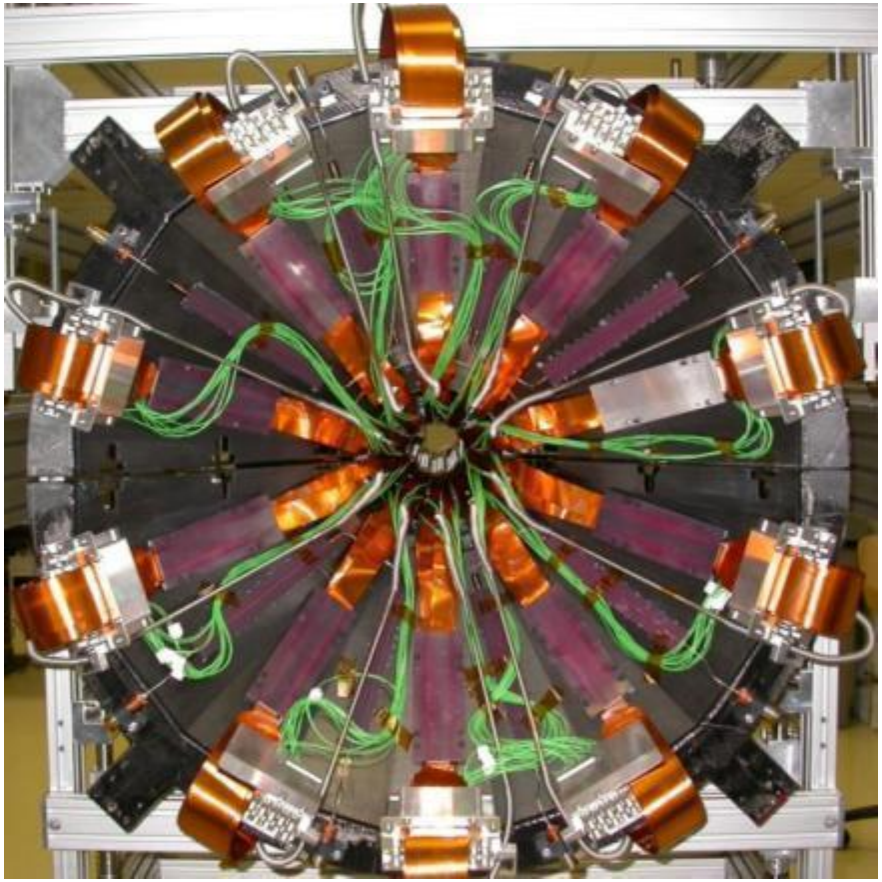
What can go wrong?

- Almost everything
  - Based on the experience:
  - Cooling since WA97: nitrogen sub-cooled with dry ice
  - High density and so large power consumption
  - Mechanics and Material budget
  - Cost effective → bump-bonding
  - Radiation hardness → problema in NA57 (shape “mezze lune”)

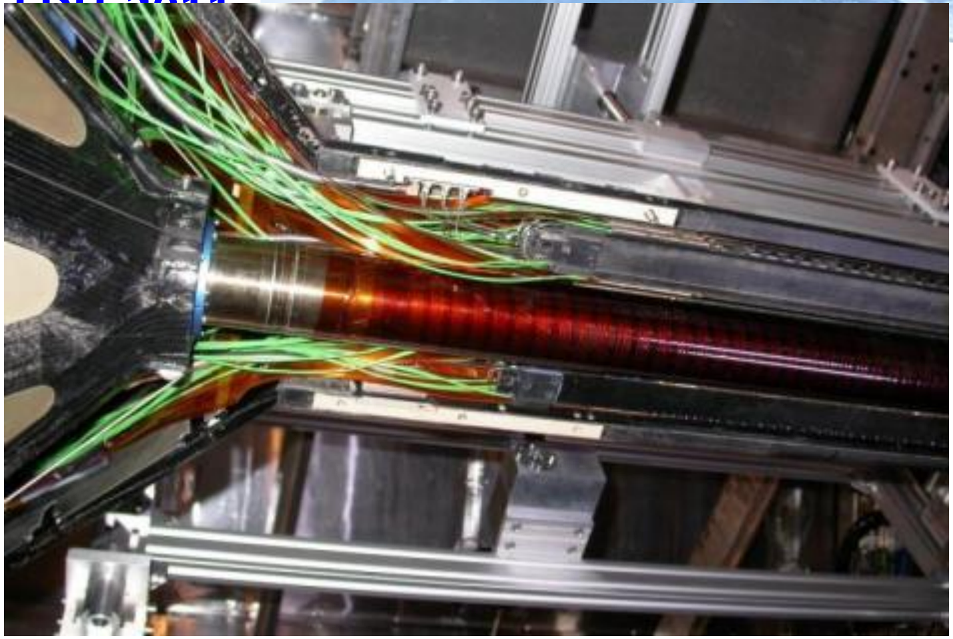
SPD assembly

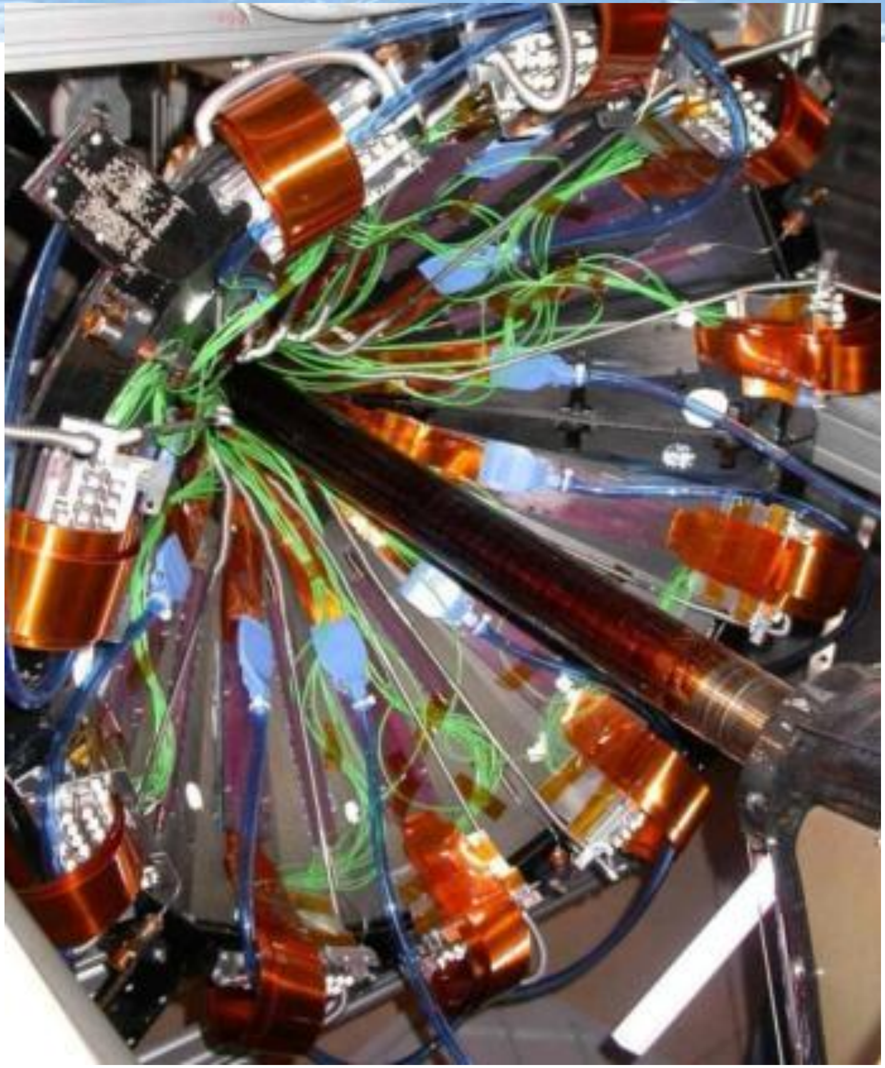
- 2 Half-barrels mounted face-to-face around the beam pipe made the full two layer barrel





SPD installation





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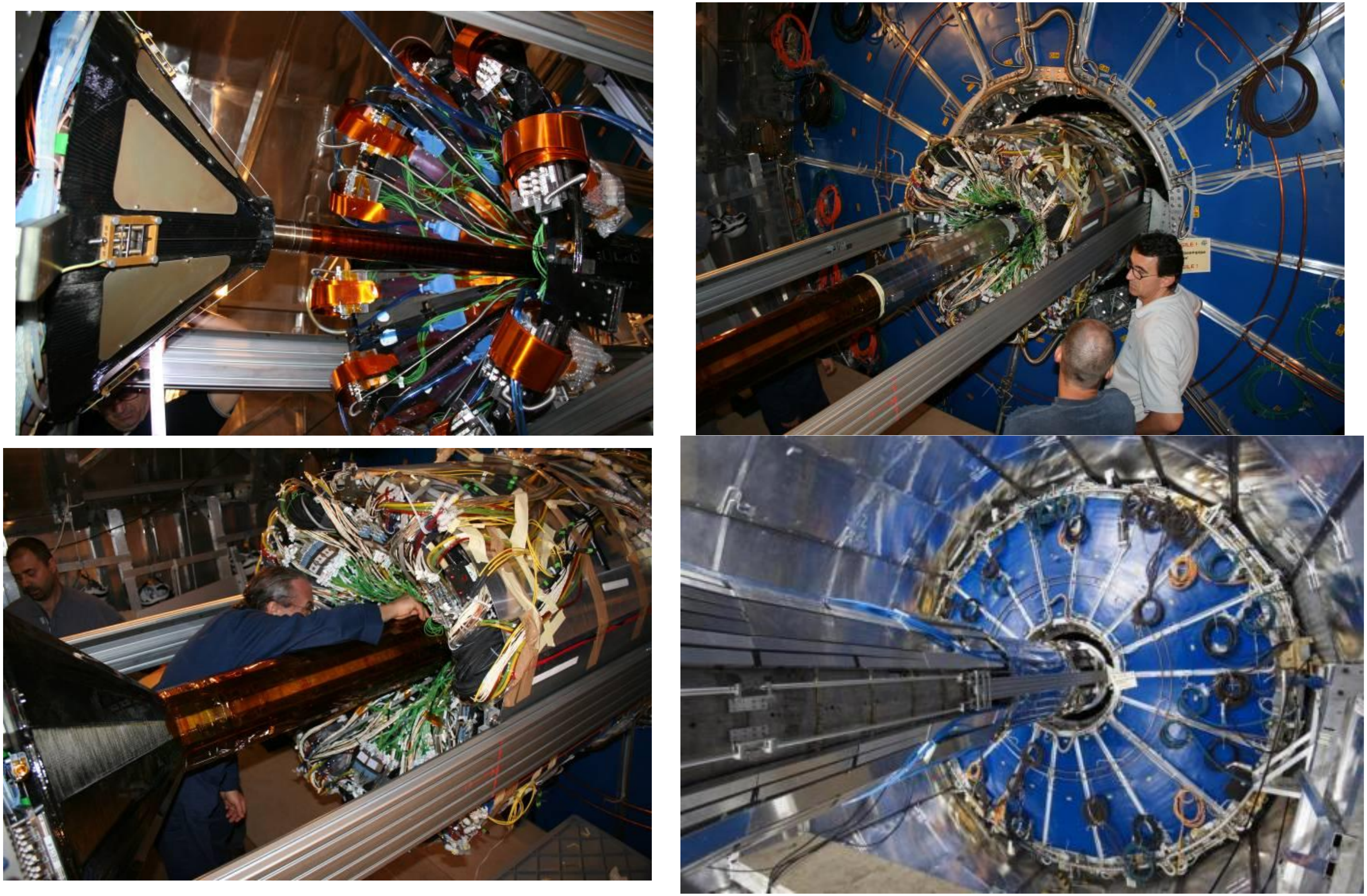
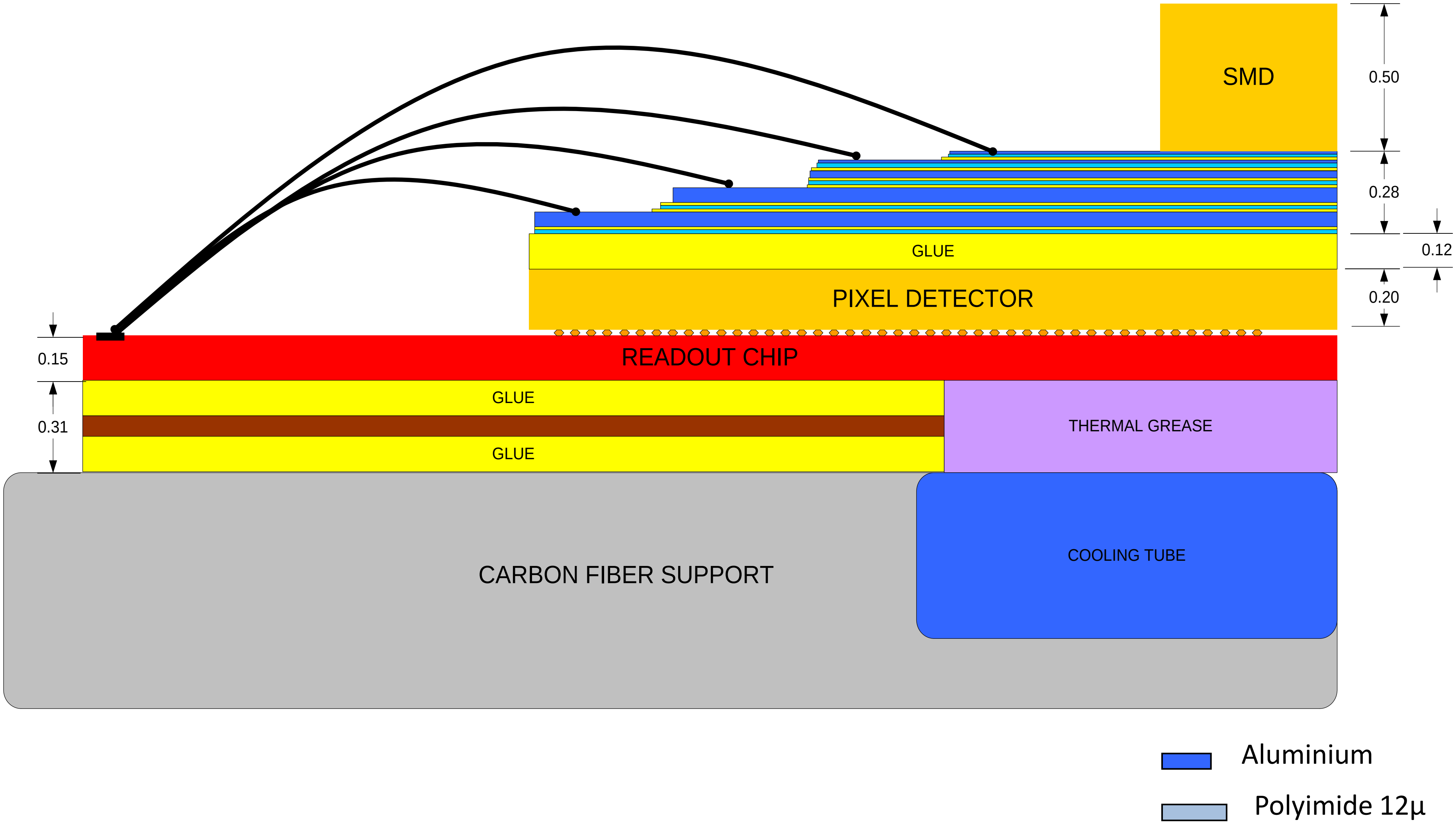
SPD installation

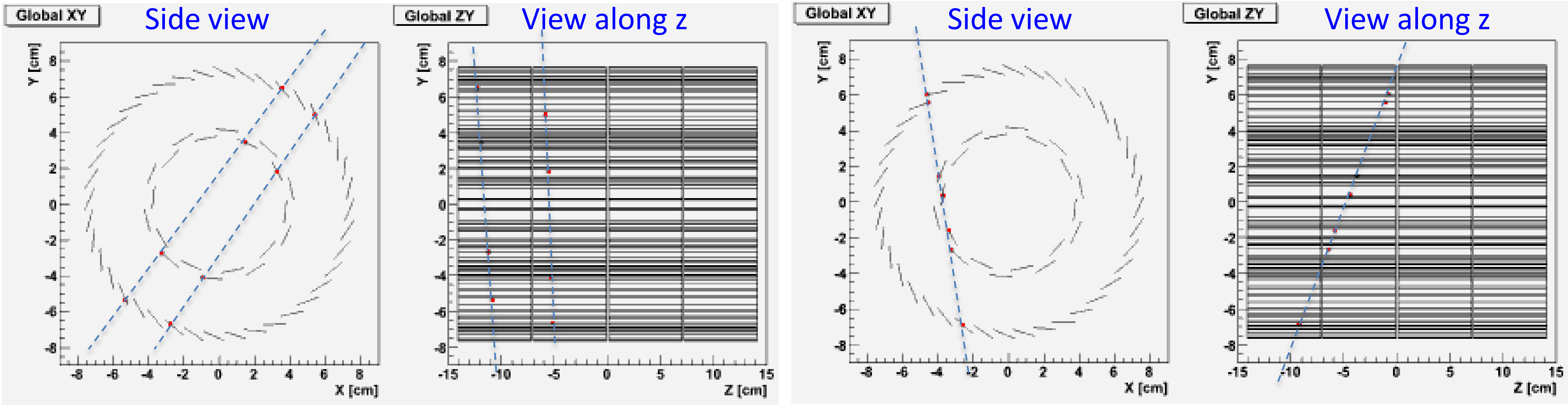


SPD Half-stave Cross Section



Alignment with cosmics

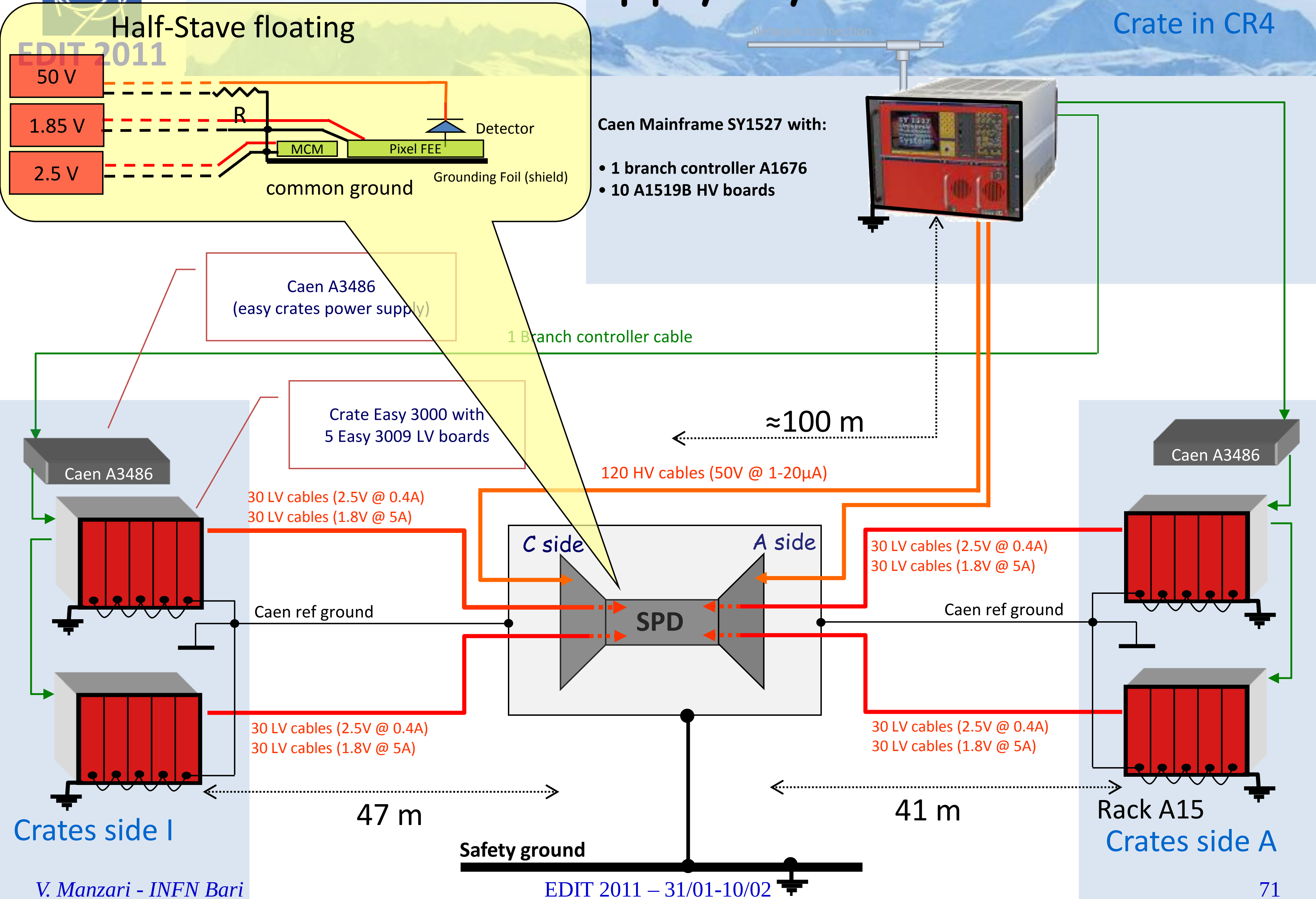
- Detector commissioning with cosmic and first LHC proton beams
- SPD prompt trigger (≈800 ns latency)



SPD Online Event Display - Cosmic Run

Self-triggered (FastOr) coincidence of top outer and bottom outer layer

Power Supply System



Half-Stave floating

Crate in CR4

Caen Mainframe SY1527 with:

- **1 branch controller A1676**
- **10 A1519B HV boards**

Caen A3486
(easy crates power supply)

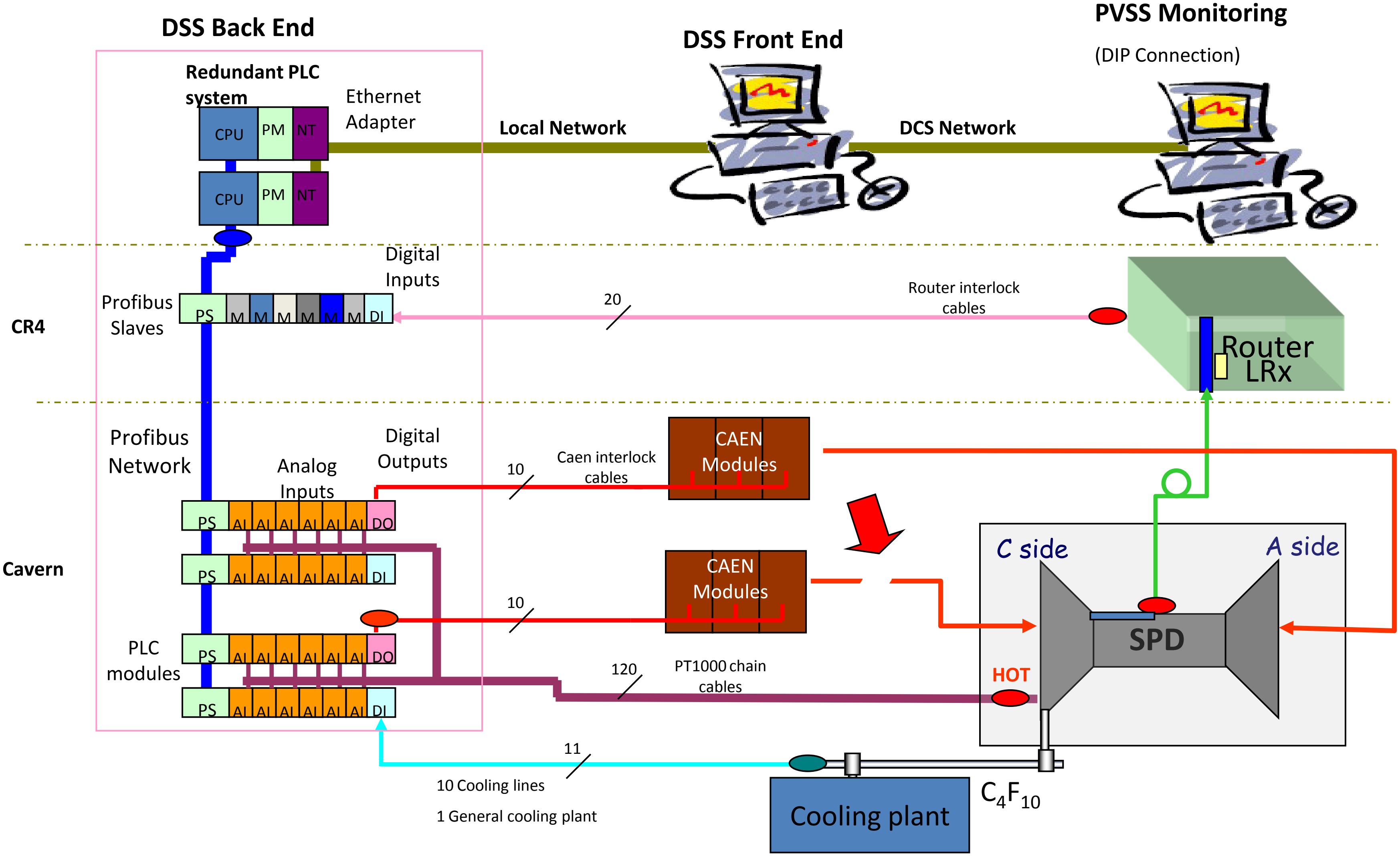
Crate Easy 3000 with
5 Easy 3009 LV boards

Crates side I

Rack A15
Crates side A

EDIT 2011

Interlock System

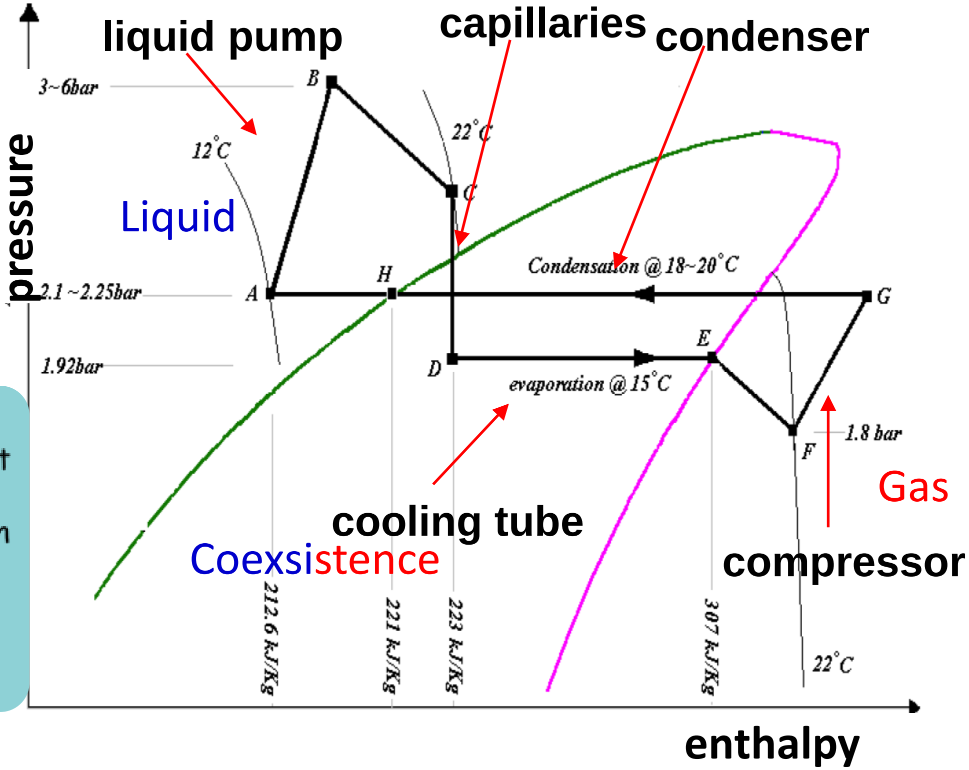


Cooling system

- Evaporative cooling system based on C_4F_{10}
  - sectors equipped with capillaries and cooling tubes embedded in the carbon fiber support sector, running underneath the staves (one per stave)
  - cooling tubes made from a corrosion-free metal alloy (Phynox) with walls 40μm thick
  - monitoring of T and p at the plant and up/downstream the detector
  - monitoring of flow per line
  - control of liquid pressure per line

- Total power dissipation ≈1.35 kW
  - due to low mass, in case of cooling failure the SPD temperature would increase ~1 C/s

The C_4F_{10} follows a Joule-Thomson cycle (evaporation at constant enthalpy): the liquid compressed by a pump is brought to the coexistence phase inside the cooling duct by a pressure drop inside 0.5 mm internal diameter capillaries. Heat abduction through phase transition happens inside the cooling tube at 15-18 °C (~1.9-2.0 bar), then a compressor raises the pressure pushing the gas towards a condenser, where the liquid phase is re-established through heat transfer to cold water (~5-10 °C)



Alignment with cosmics

- Cosmic data taking for detector alignment
  - Pixel Trigger:
    - coincidence **Top Outer Layer AND Bottom Outer Layer**
    - rate: 0.18 Hz