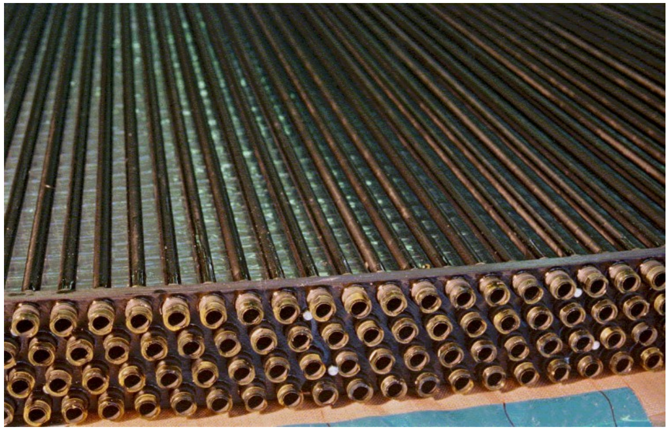
Everything electronics engineer always wanted to know about Straw detectors and their electronics

... and never dared to ask

Collection of talks, presentations, papers, experiences, etc.
from various people including myself

What's all this STRAW DETECTOR stuff, anyhow?

- Sort of proportional drift tube
  - Tracking detector
- Difference
  - Low material budget
  - Smaller in diameter (2-10 mm)
  - Large number of detector elements crossed by particle
  - Can be used also for particle identification (TRT)
  - (tuned to sustain high particle rate)
- How to recognize
  - Fancy detector which looks like a stock of hay
  - Distributor of straws for drinking your favorite potion

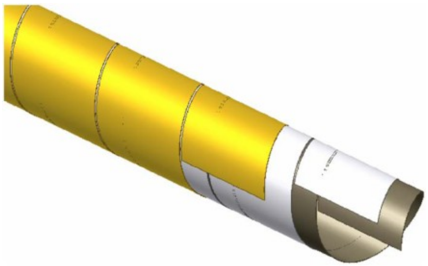


Where are straws used?

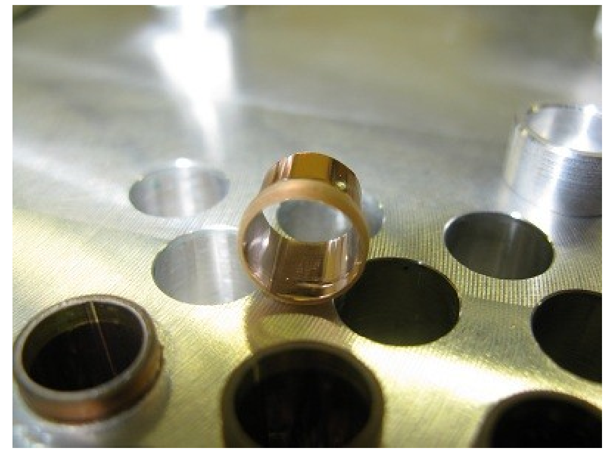
- Many experiments
  - DELPHI, HERA-B, FINUDA, COMPASS, LHCB, **ATLAS, NA62**,…
- Different environments
  - High radiation > 10 MRad (TRT)
  - High rate > 20MHz/straw (TRT)
  - Low material budget < 0.5% rad length (NA62)
  - Resolution of single straw < 50um (FINUDA)

Straw production

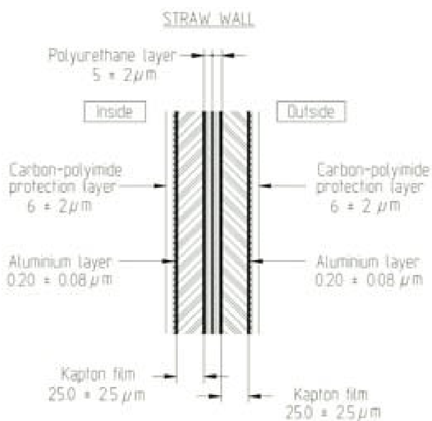
Glueing 2 overlapping strips (COMPASS)

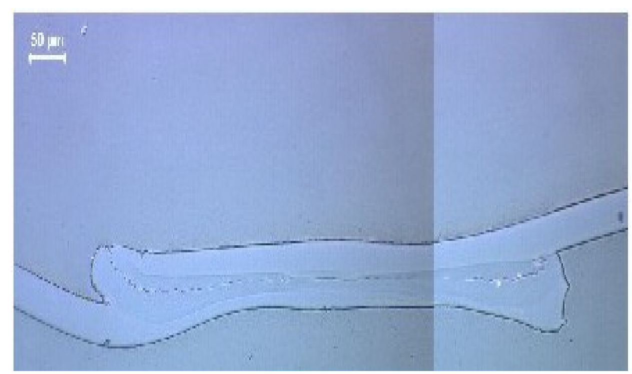


1 strip ultrasonically or thermally welded (NA62)



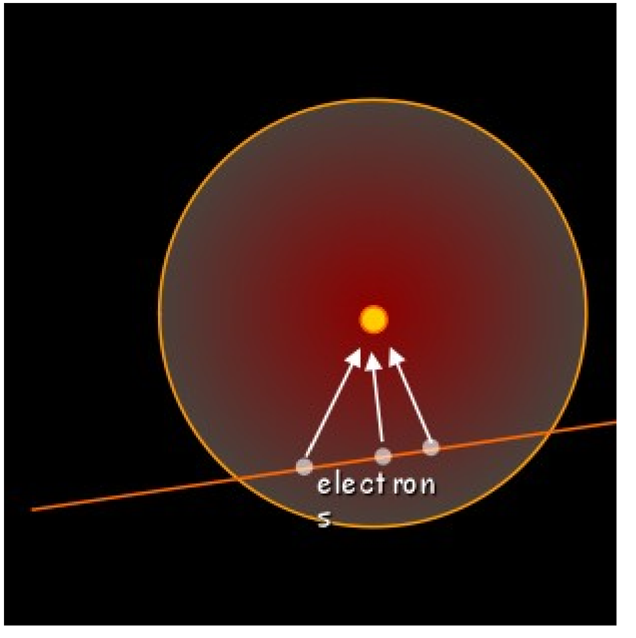
Glued and reinforced by carbon fibres (also improving cathode resistivity)





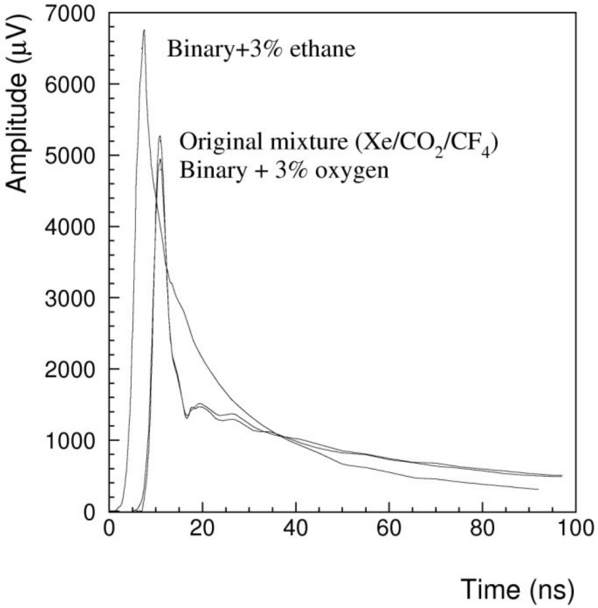
Signal formation

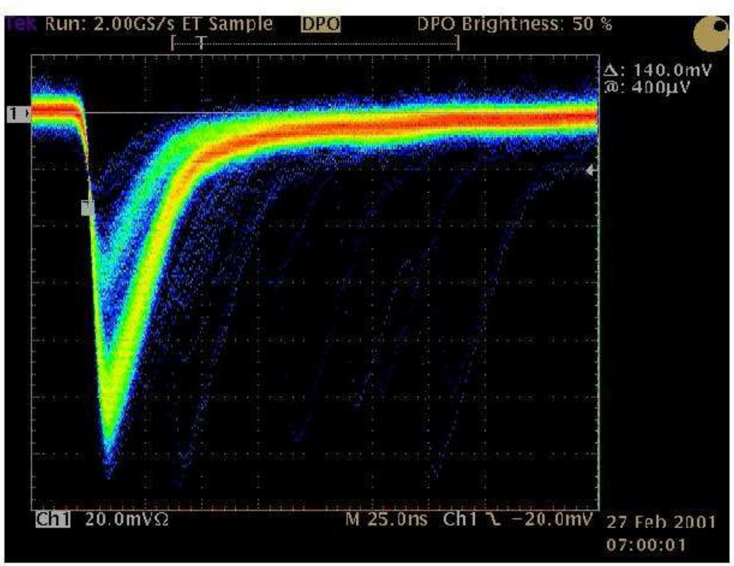
- As any other proportional chamber
- 1/(t+t0) per cluster
- !!DANGER!!
  - This formula has been derived assuming constant mobility of ions (NOT velocity)
  - The first 10ns -~100ns differ depending on gas and electric field
  - The tail follows 1/(t+t0)
  - The tail lasts until last ion arrival, can be ~100-s microseconds
- With the characteristic shaping time of ~20ns, one uses only ~5% of total charge



Signal formation

- Electronegative gases (CF4, O2) are changing the signal shape
- Less charge then expected
- Right -> ATLAS/TRT

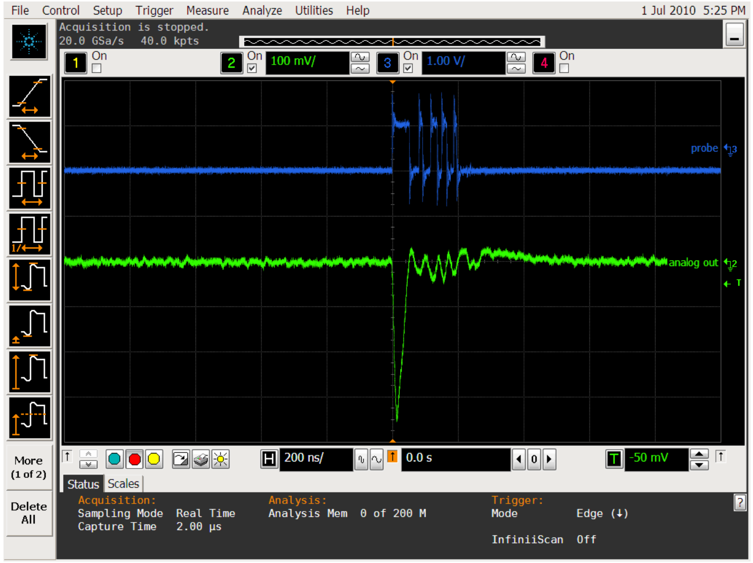


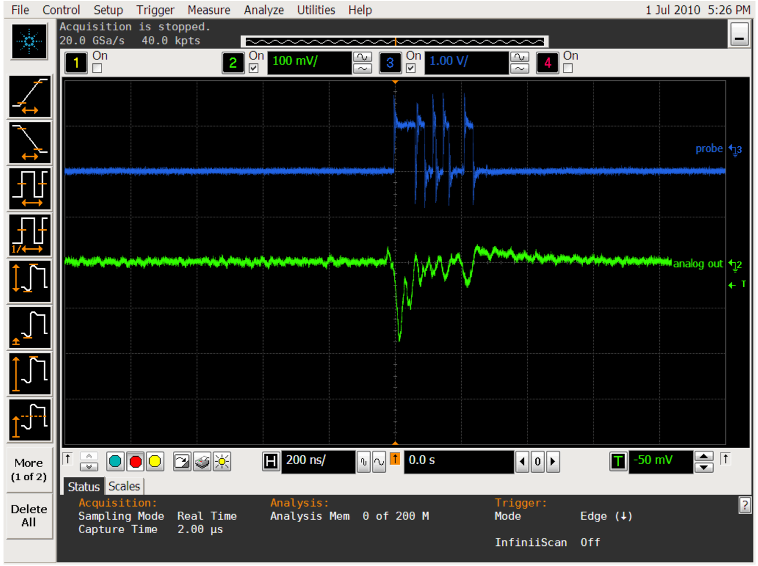


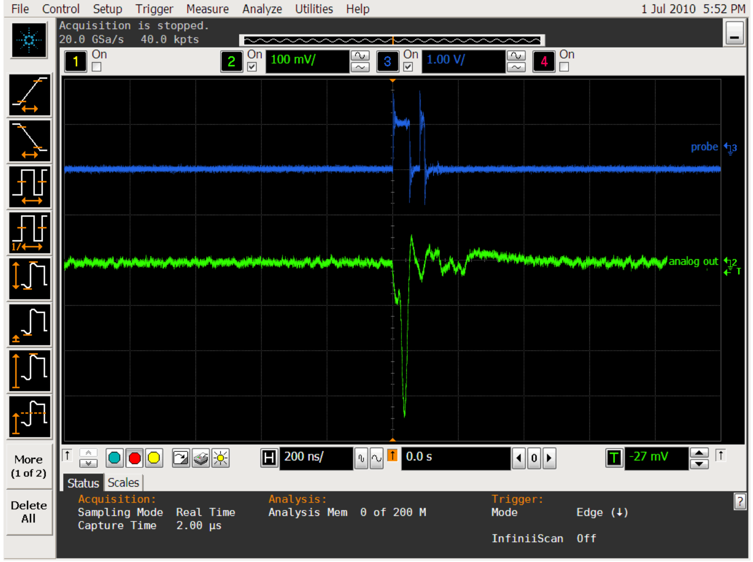
Ar/CO2 'follows' 1/(t+t0)

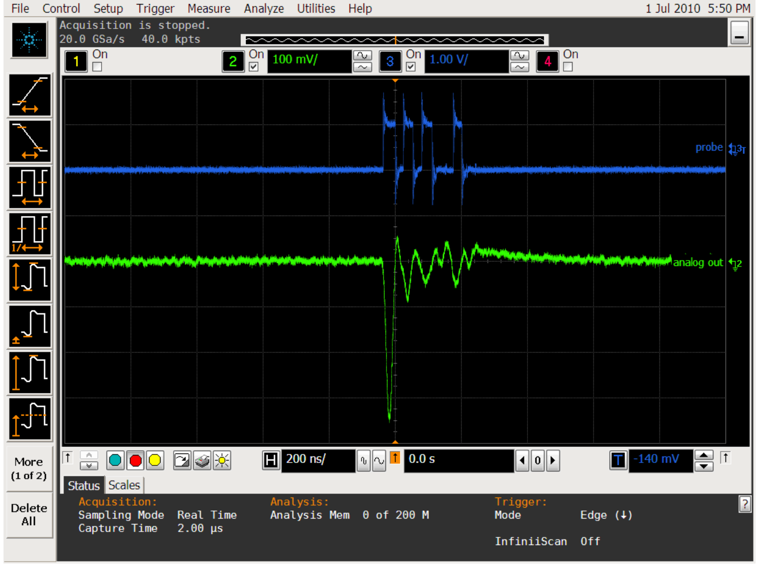
(COSY-TOF straw 1m/1cm)

Slow gas analog and comparator outputs CARIOCA with NA62 straw



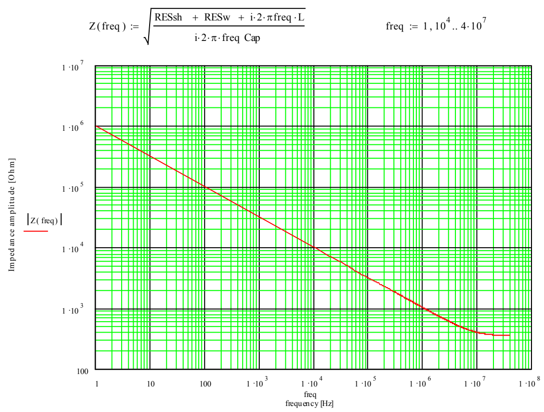


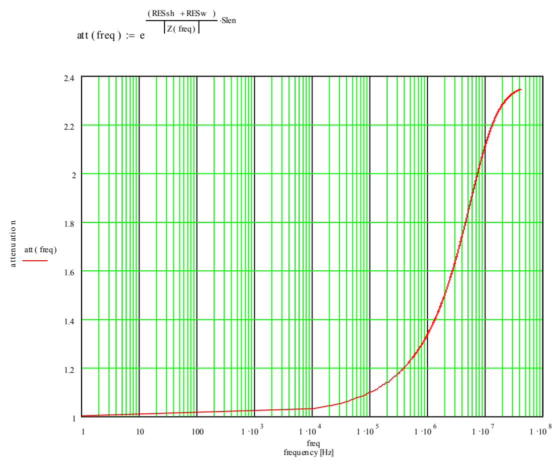




Straw as a transmission line

- Range of lengths 10cm -> 5m
- VERY lossy transmission line, resistance of Cathode/Anode 10->100 Ohms
- Due to (non-)thickness of cathode metal and small diameter of anode wire the skin effect does not exist
- Quantum physics at work as often there are only 10-100 atomic layers of metal atoms, resistivity can’t be calculated from thickness
  - NA62, 15 Ohms calculated and 130 Ohm measured for 60nm Cu + 20nm Au





- Impedance changing dramatically in useful frequencies

  ~1000 (1 MHz) -> ~350 Ohms (20 MHz)

- Attenuation very high in useful frequencies

  2.3 at 20 MHz

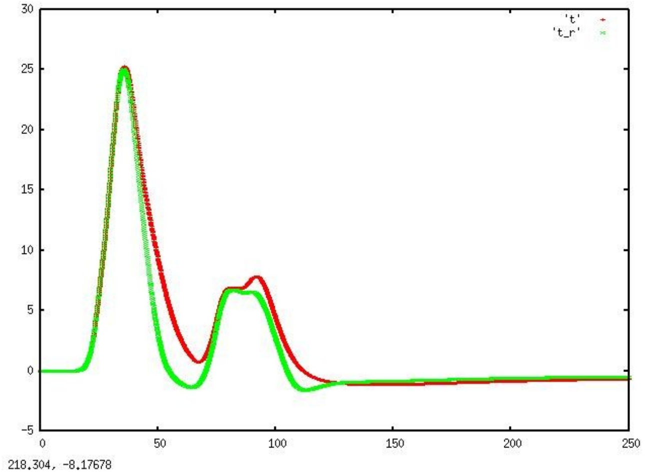
- Phase shift will create dispersion

  -lower frequencies propagating slower then high frequencies

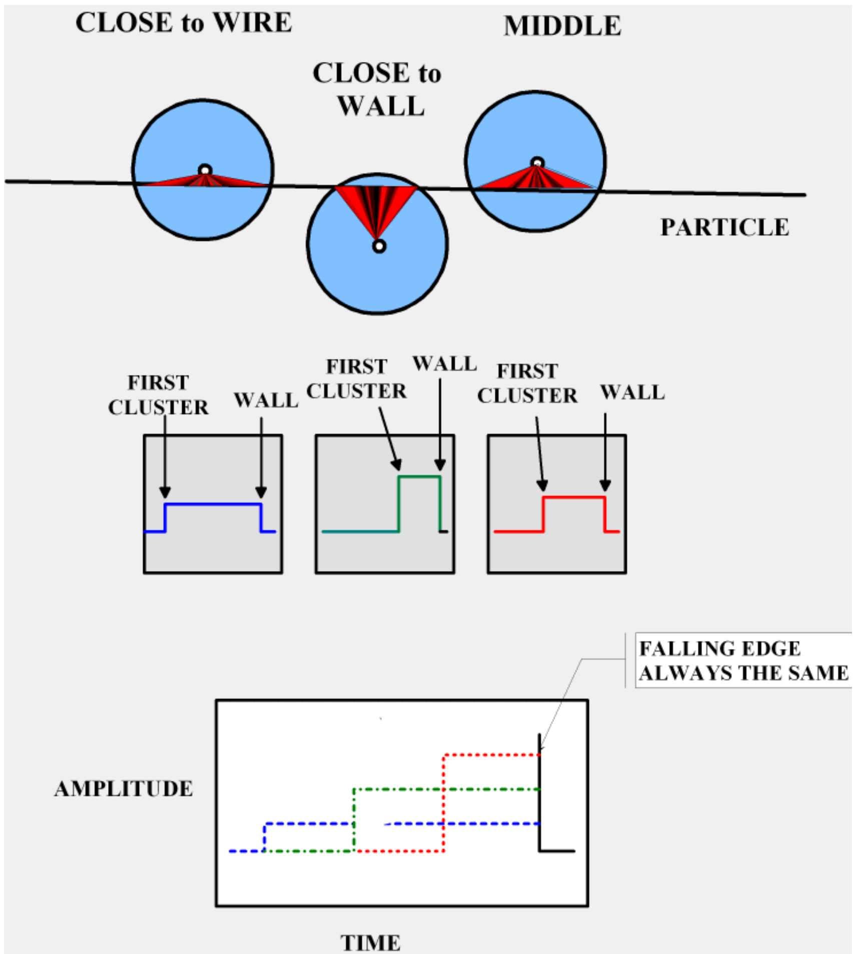
Straw termination

- Termination could be used to improve signal amplitude and spread BUT can have also opposite effect!
- Far end open
  - signal created at this end of straw reflects back in right polarity and helps to increase signal amplitude at the preamp (compensates partially attenuation losses)
  - Signal created close to preamp will reflect back and return to preamp after ~ 15 ns, attenuated almost 6x
- Far end terminated with high impedance ~1->10 kOhm
  - Can help to eliminate long tails (lower frequencies)
  - Does not influence very much high frequencies
- Close end connected directly to preamp (through protection resistor)
  - Can increase signal amplitude if Rin + Rprot < Zstraw
  - Signal will reflect back in opposite polarity, input current to charge sensitive preamplifier will be higher
- Termination by "real" resistors can increase the noise by factor 2!
  - 300 Ohm parallel resistor would be the most dominating noise source

Simulation of the effect of signal reflection from CARIOCA low impedance input for NA62 straw 2.1 meter long. Red – without reflection



How does it work?



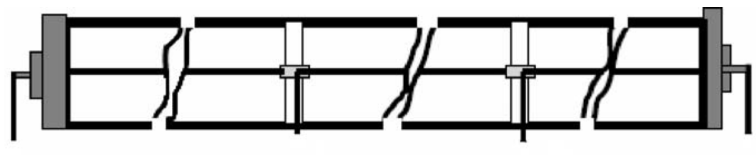
- Falling edge has the same time for all straws on track.
- Rising edge gives the arrival time of the first cluster
- The closer is the track to the wall, the bigger is the signal (clusters closer)
- Don’t want to see clusters => shaping must be chosen in relation to gas properties
- Tracks from drift time measurements

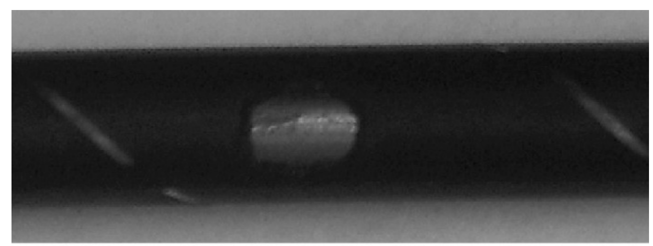
Readout concept

- Precise tracks from drift time measurement.
  - arrival of the first cluster
- Track selection, identification and validation from the trailing edge
  - Arrival of the last cluster
  - ID attached to trailing edge should be used for matching with trigger ID
  - All straws with matched IDs within time window (for straw propagation time) are on the track
  - Straw propagation time should be subtracted from leading edge before calculating particle position
- Trailing edge can be used for crude z-by-time measurement to help track reconstruction
- Trailing edge can be used in fast trigger or as an anti-coincidence (VETO) on multiple tracks

Improving high rate capability

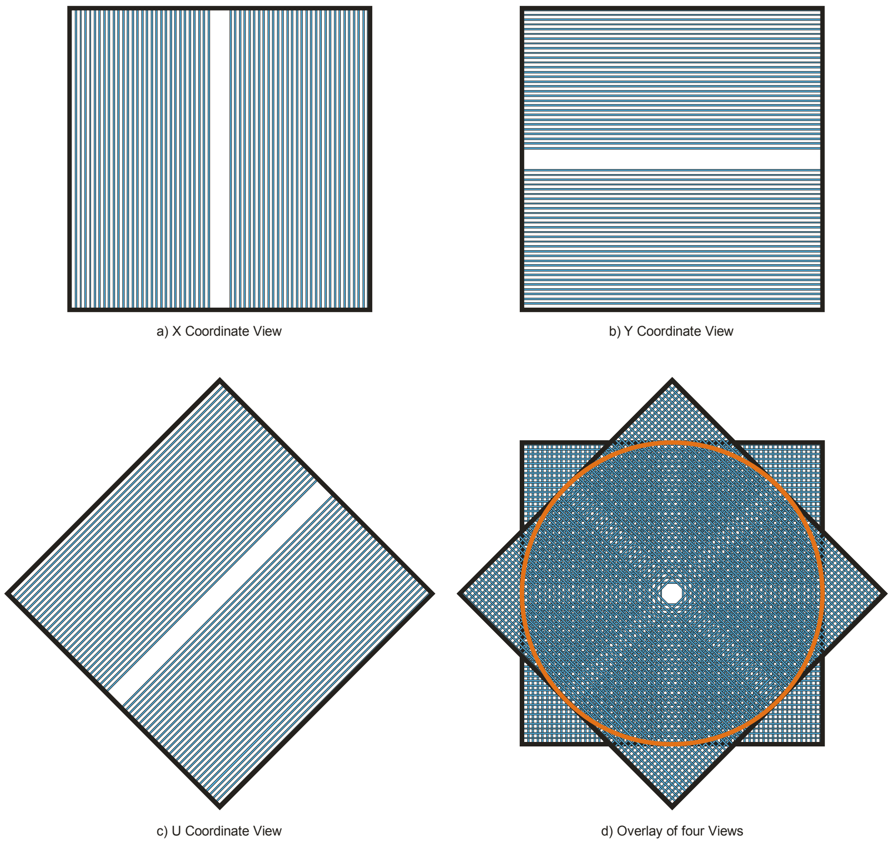
- Smaller diameter
  - Less particles
  - Less charge in gas volume
  - Shorter collection time
- Segmented straw
  - Cathode segmentation
    - Highly resistive inner coating
    - External metallic rings on which signal is induced
    - Never saw/heard functional prototype
  - Anode segmentation
    - ATLAS/TRT barrel 2 sections
    - Ongoing work for more to improve high-rate capabilities
- Using faster gas





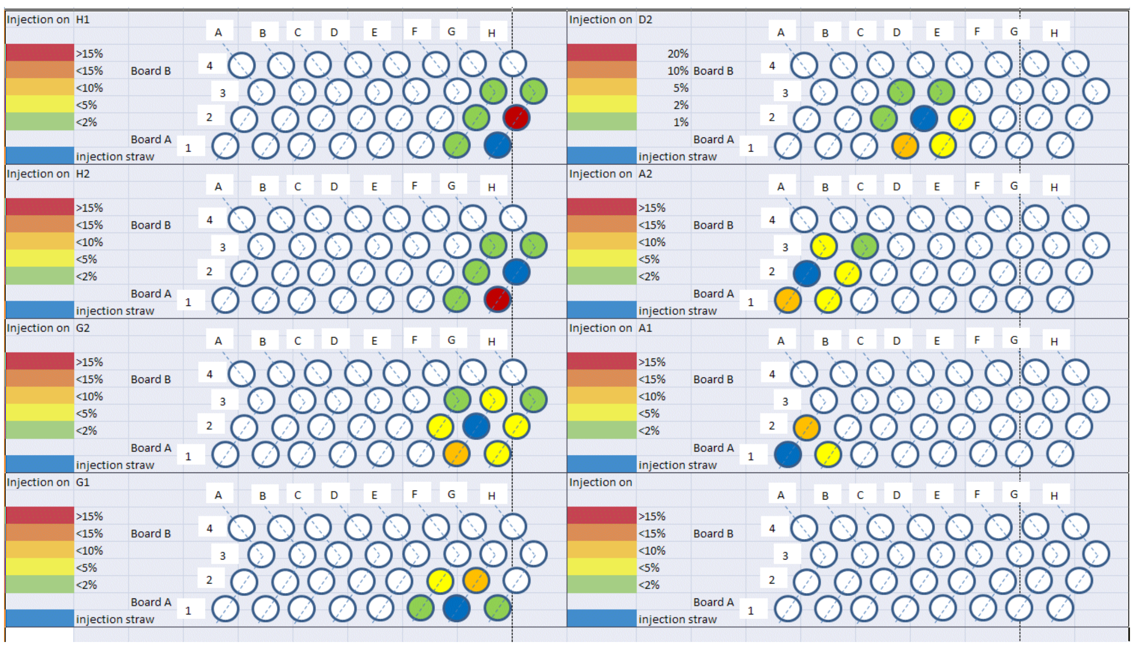
Z-coordinate measurement

- Another layer of straws at different angle
  - The best method commonly used
  - On the right, 4 planes of straws x,y,u,v for NA62
- Segmented straw (used also for high rate)
  - Cathode segmentation
  - Anode segmentation
- Z- by time
  - Measuring signal arrival at 1 or both ends
  - Depends on gas, signal formation is comparable with propagation time



Crosstalk

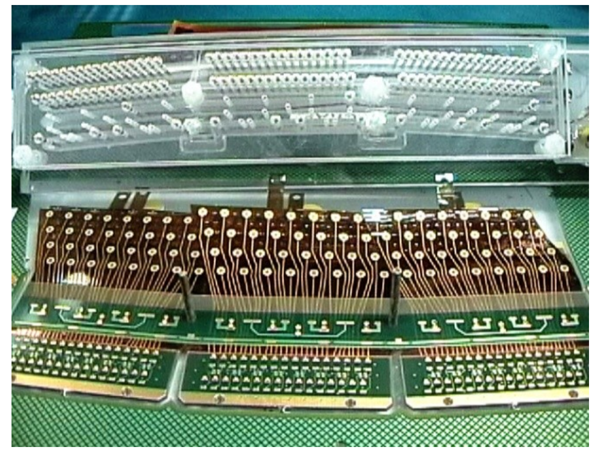
- 3 types, conductive (usually dominant), capacitive, inductive
- Straw-to-straw usually < 1%
- Rather poor against external source due to resistive cathode
- Connections from straws to frontend and frontend itself usually dominant



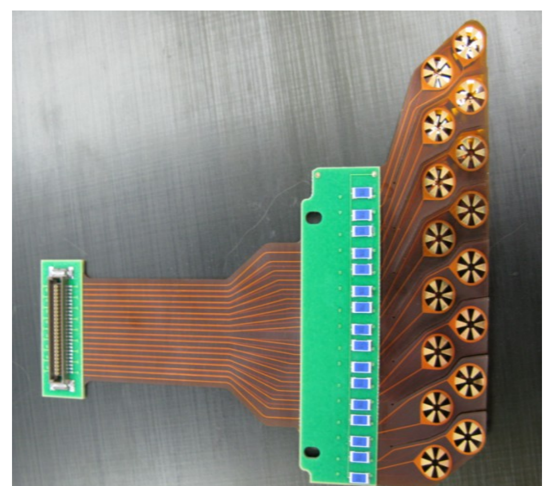
Measurement of NA62 straw crosstalk
- Only neighbouring straws are victims
- the problem was found in web layout for this case

Connecting straws

- Most popular method is using ‘web’ circuits
  - 2 layer Kapton (polyimide) flex circuit
  - For cathode, bigger petals are pushed inside straw tube by endplug,
  - For anode, the wire is terminated with pin passing through endplug and piercing smaller petal
- Some detectors
  - use wrapped springs to connect cathode
  - Anode by loose wire



ATLAS/TRT



NA62/STRAW

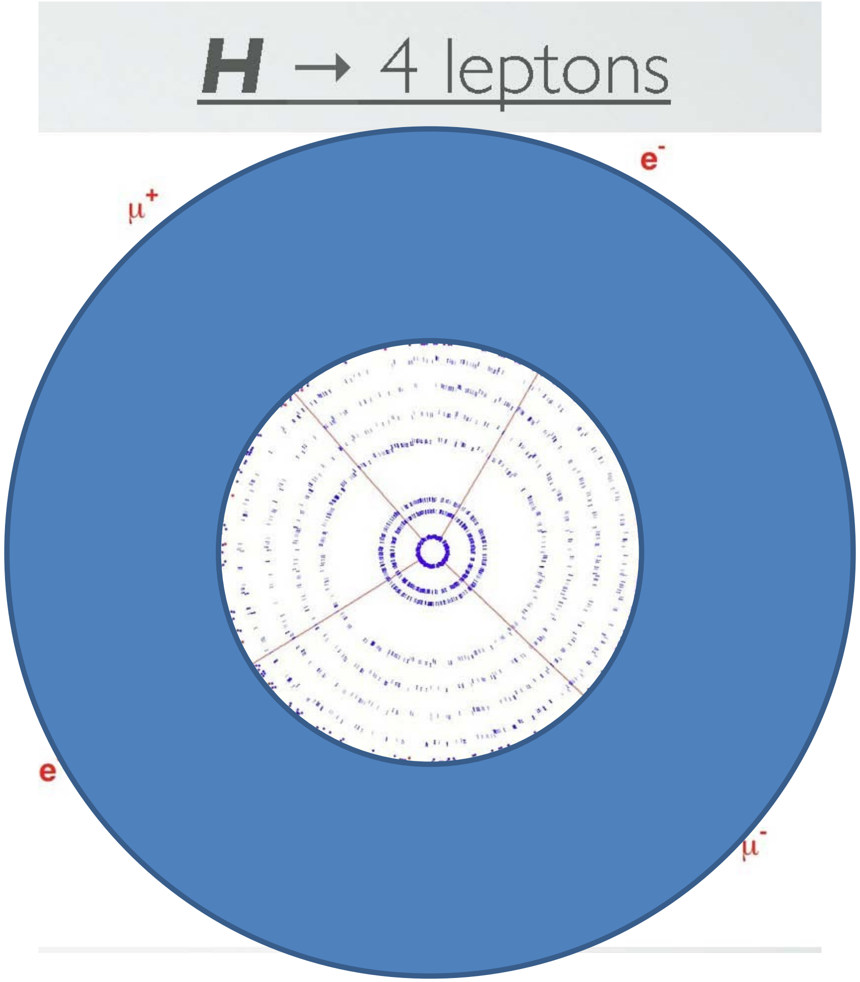
Frontend requirements

- Some as for other gas detectors
  - Tail cancellation
  - Shaping related to charge collection time and required level of noise
  - Usually shorter shaping for time measurement
- Straws are used mainly for measuring the time information
  - If needed, ToT (Time over Threshold) is used for estimating the amplitude (ATLAS/TRT)
- Difference
  - Noise-less termination of straws
  - Preamp designed for input impedance
    - ASDBLR (ATLAS/TRT) ~120 Ohms
  - Reflections can play important role for a design
  - The usual capacitance model of the detector does not work very well for longer straws
    - RC element
    - Lossy transmission line

Straw detector examples

- ATLAS/TRT
  - Unique detector, till now the only one of this kind
  - Provides tracking AND electron identification in high rate ATLAS inner detector environment
  - Used also for finding heavily ionising particles with ToT
  - Major contributions to ATLAS commissioning:
    - **FastOR** cosmics trigger provided high rate of tracks for Inner Detector
    - Used good track time resolution (~ns) to become **timing reference**
- NA62
  - Tracking with very low material budget <0.5% RL
    - Vacuum
  - Looking for extremely rare decays 1 in 10^10 in high rate environment ~100s Mhz (0.5 MHz/straw)

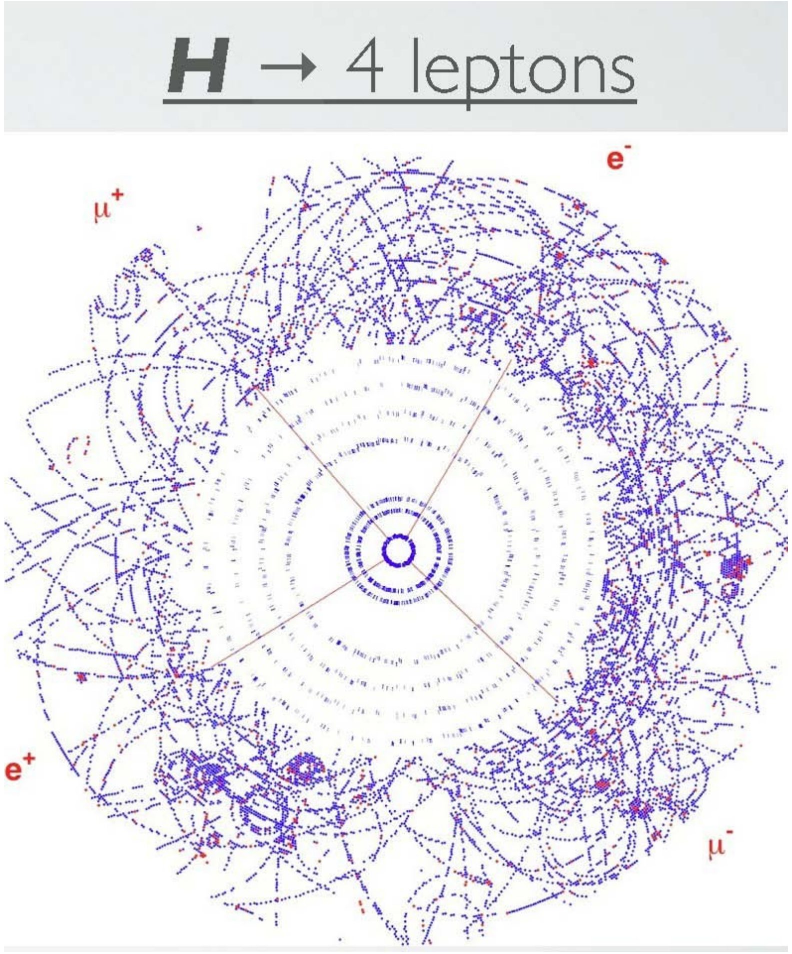
TRT acceptance to EAGLE (later ATLAS)



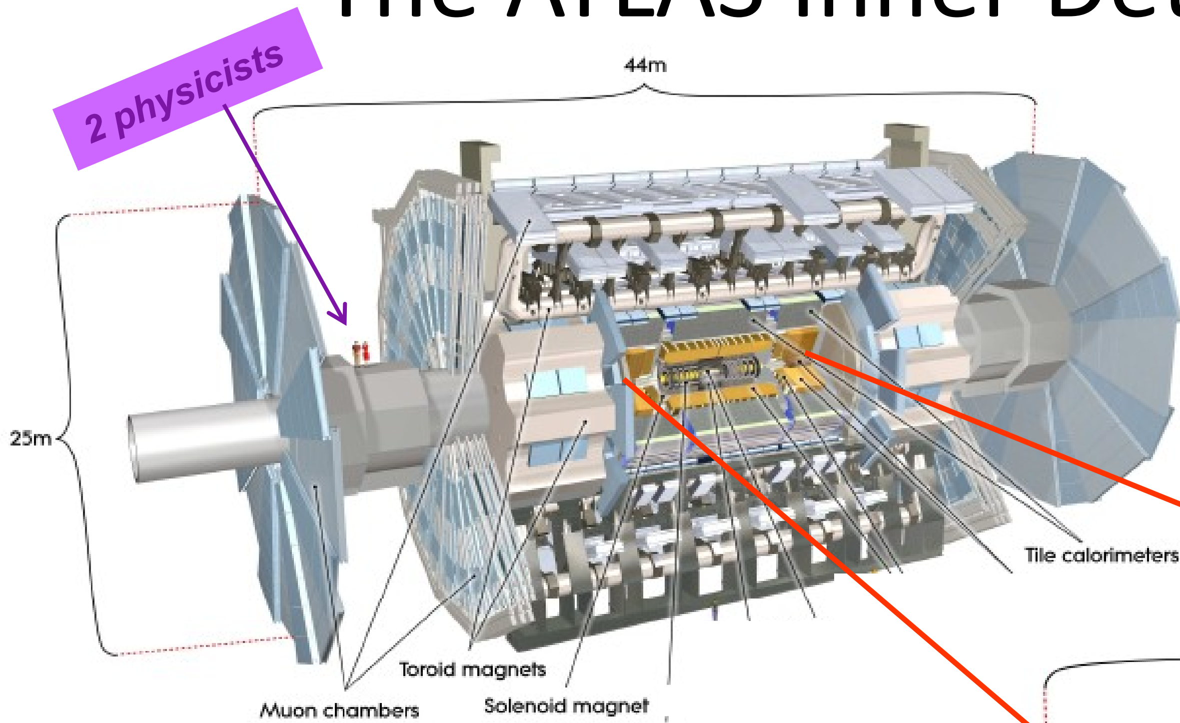
- The fairy-tale how gaseous detector took place at modern inner detector
- Meeting in Oxford (199X)
- expectation TRT was going to be rejected
- simulation of 'real' events presented
- you can see hits from Si tracker
- AND ....

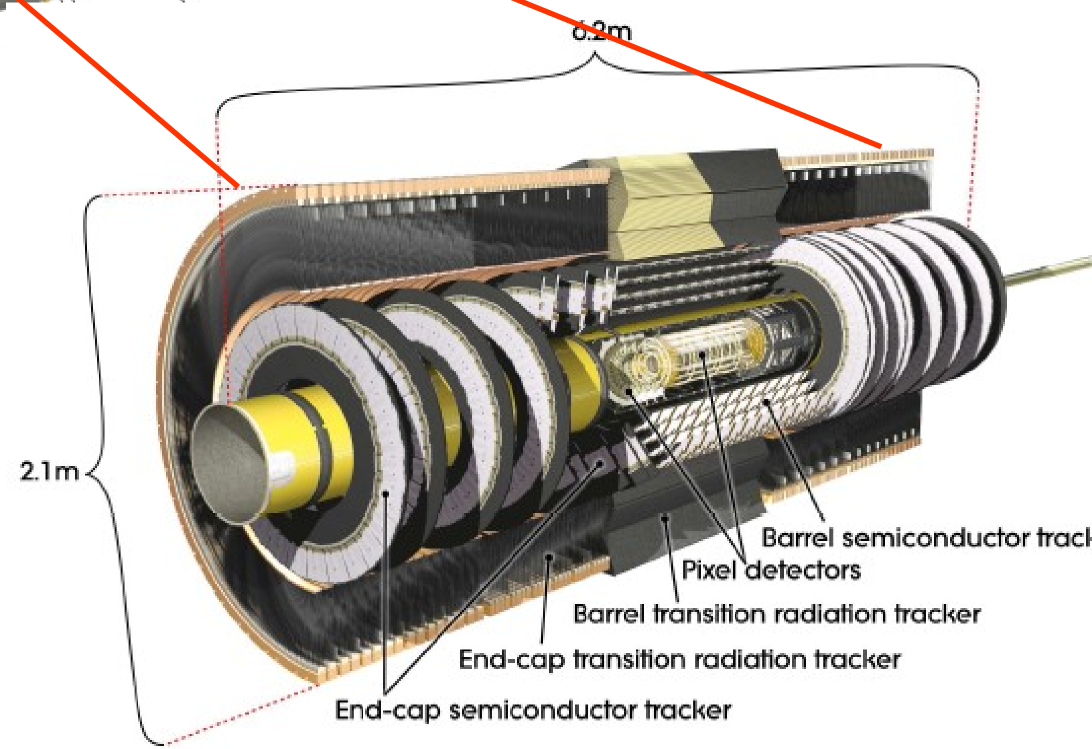
TRT acceptance to EAGLE (later ATLAS)

... Hits from TRT included
The picture became clear!
TRT providing 36 points on track



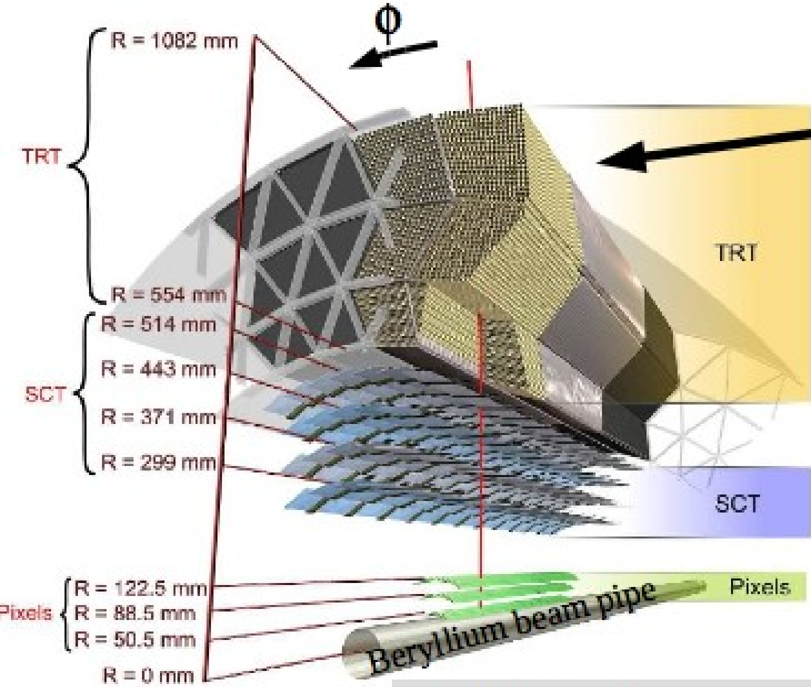
The ATLAS Inner Detector (ID)





- Provides charged particle tracking for particles above 0.5GeV, $|\eta| < 2.5$
- Electron identification for particles with $|\eta|<2$ and $0.5 < p_T < 150$ GeV
- Surrounded by solenoid B = 2T
- Consists of Pixel detectors, Semiconductor Tracker and Transition Radiation Tracker (TRT)

The Transition Radiation Tracker (TRT)

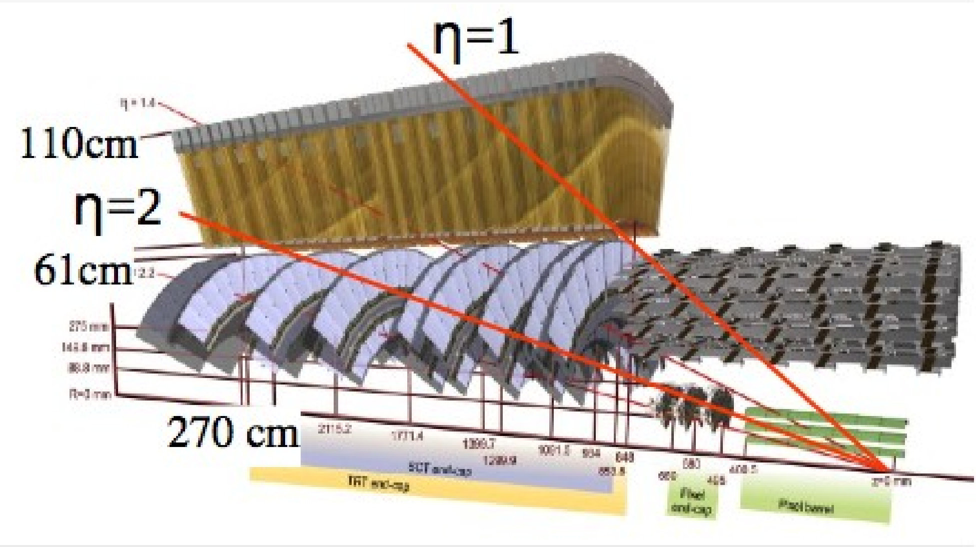


TRT barrel

- 3 * 32 modules
- 1.44 m straws parallel to beam axis
- wires electrically split in the middle to reduce occupancy (~1.5cm dead region)
- each end read out separately
- 105088 readout channels total
- 2 triangular front end electronics boards per module

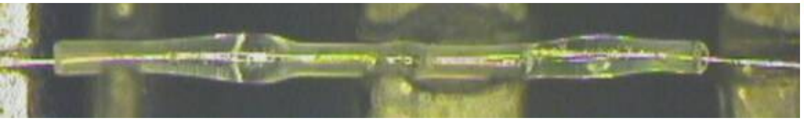
2 TRT end-caps, each with

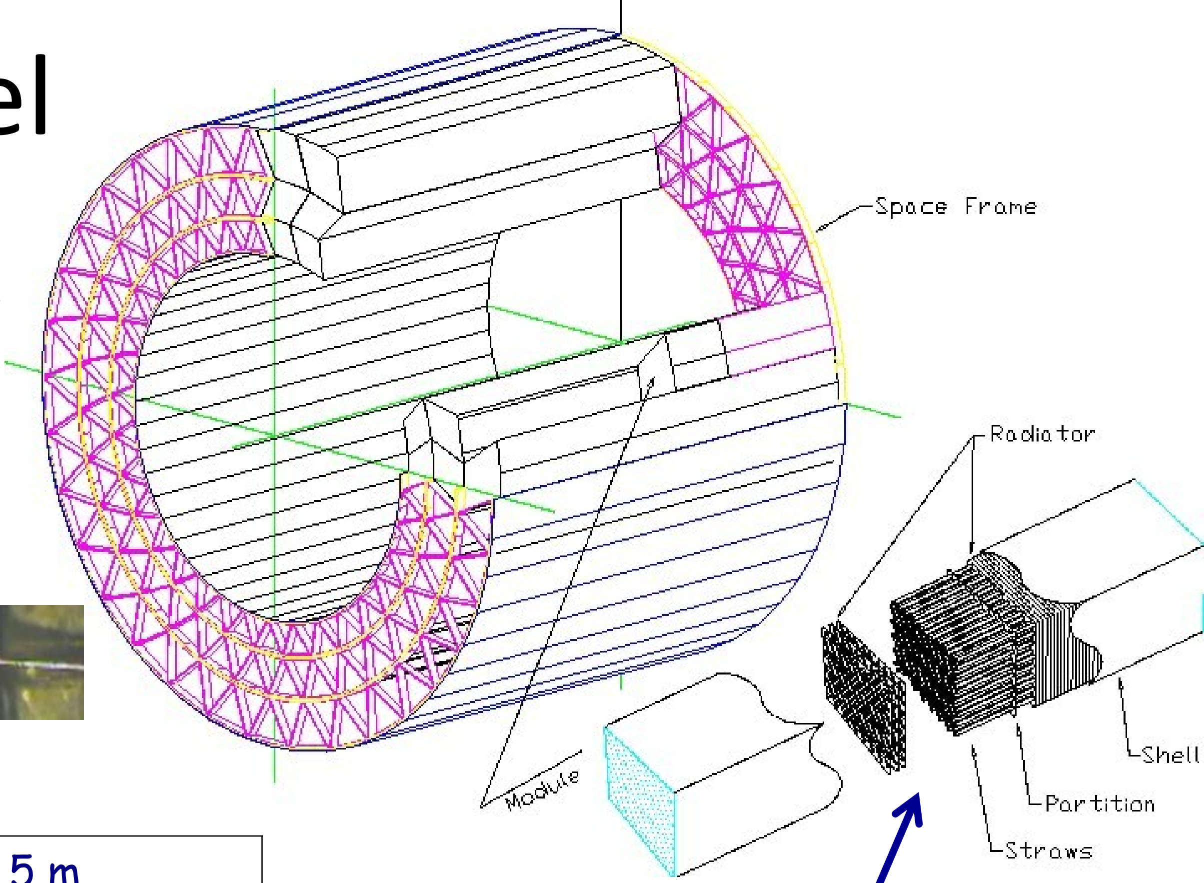
- 20 “wheels” with 8 layers of straws each
- 39cm long radial straws
- 122880 readout channels



The TRT Barrel

- 3*2 module types, forming 3 rings of 32 identical modules
- 52544 straws total
- **glass wire-joint** provides independent read-out at either end

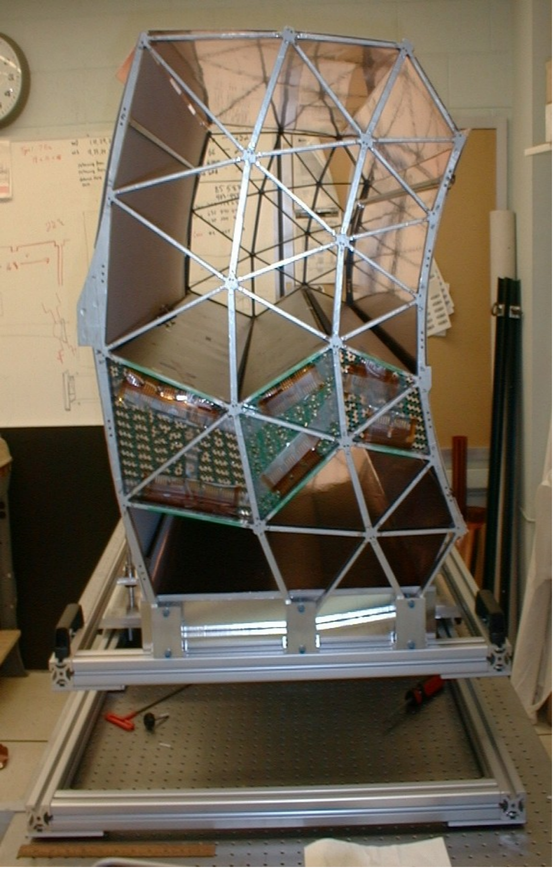


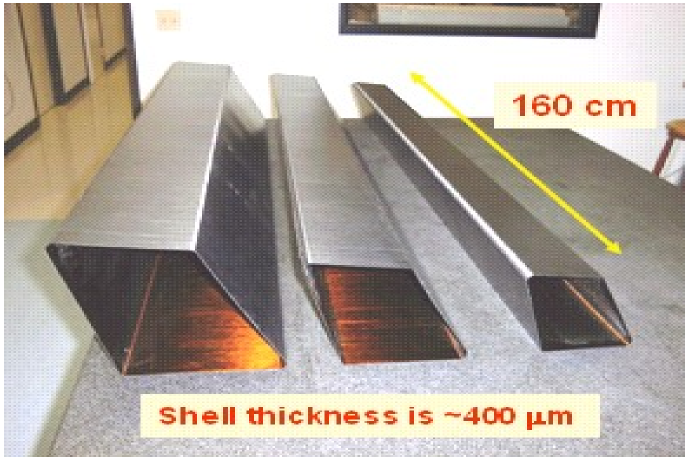


Module Length	1.5 m
Sense Wire Length	2 x 0.75 m
Straw Diameter	4 mm
Wire Diameter	30 μm
Distance between straws	6.8 mm
High Voltage Grouping	8 straws

Basic Module Design

Straws are embedded in oriented fibers and supported by dividers and endplates, which are connected along the module by a carbon-fiber shell



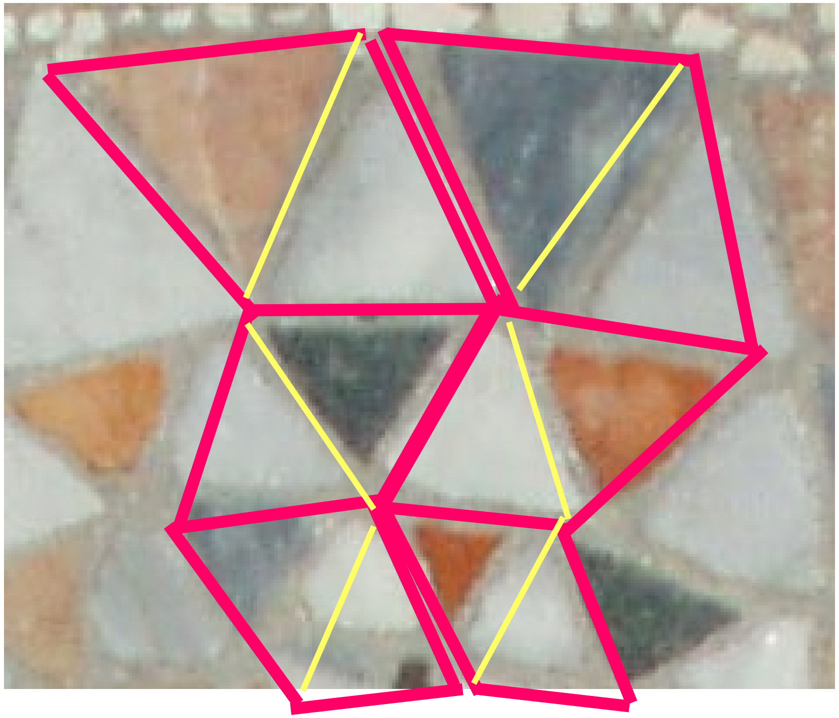

160 cm
Shell thickness is ~400 µm


new event

The barrel TRT – a classical design

ATLAS

12th century mosaic.
Otranto cathedral, Italy



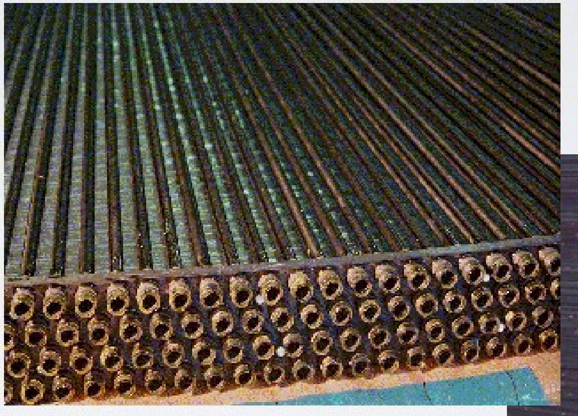
“Original” classical design: 4 layers

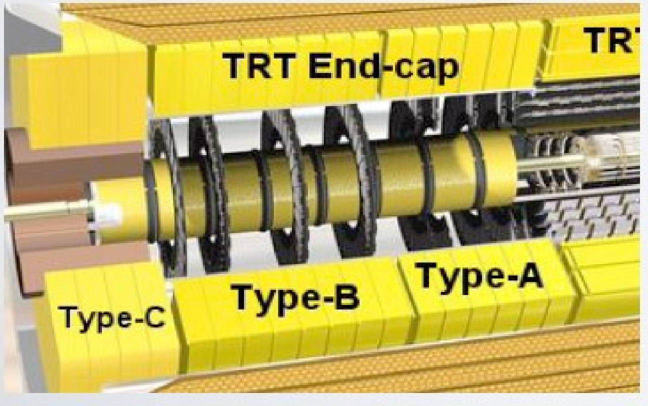
Simulation of a cosmic particle?

END-CAP ASSEMBLY

<u>One End-cap</u>

- 8 A wheels, 6 B wheels
- 160 planes of 768 straws per plane
- 122,880 straws
- Radiator foils placed between each plane

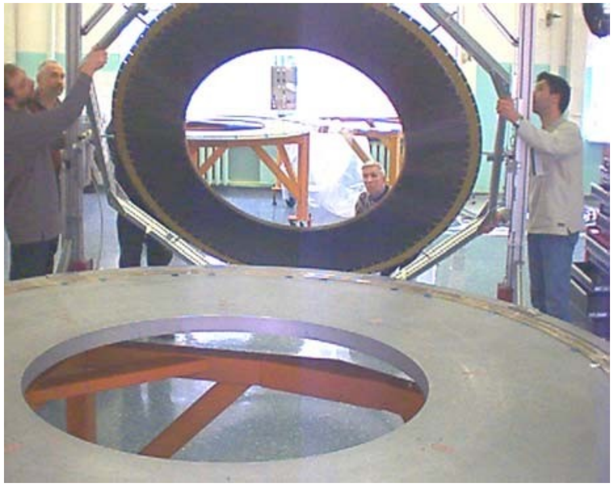




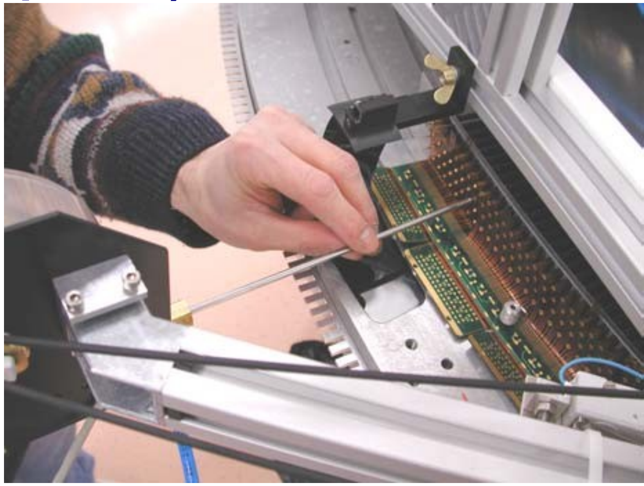
End-cap wheel production

(basic element: wheel with four wire planes)

Installation of straws
(tests leak tightness)

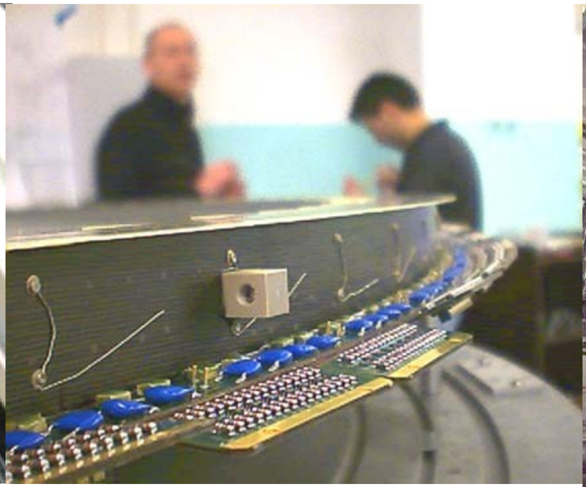


Transfer of wheel…

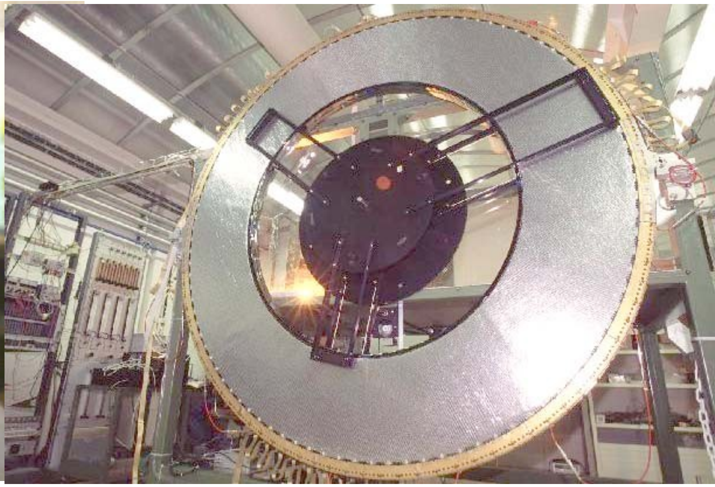


…to string wires

Fixating and connecting wires
(tests wire tension & HV)



Sealing of wheel
(tests leak tightness & HV)



Final acceptance tests
(test wire centricity etc.)

Tests of the gas quality for endcap wheel and refilling

CONDITIONS FOR TRT OPERATION

Counting Rate per wire	20 MHz
Ionization Current Density	0.15 μA/cm
Ionization Current per wire	10 μA
Power dissipated by ionization current per straw	15 mW
Total ionization current in detector volume	3 A
Total dissipated energy in the detector volume from ionizing particles	5 kW
Charge collected over 10 years of LHC operation	10 C/cm

Total Radiation Dose after 10 years

Neutrons	10^{14} n/cm^2
Charged Particles	10 MRad

Particle Flux at 1m from IP

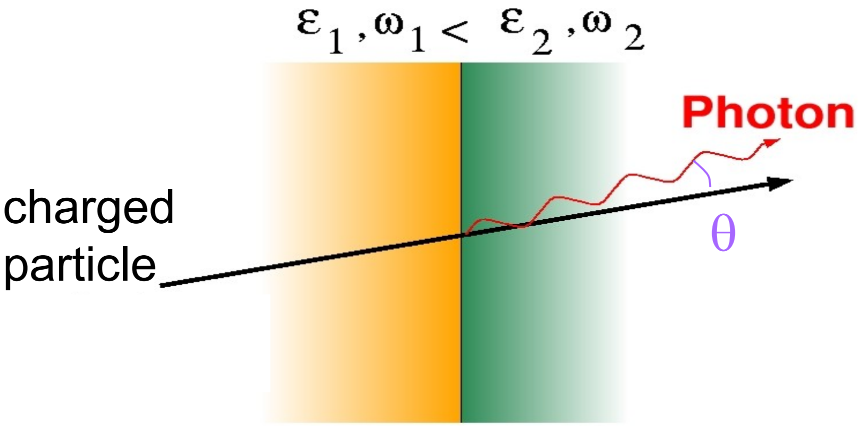
Charged	10^5 hadrons/cm^2 sec
Photons	10^6 photons/cm^2 sec
Neutrons	10^6 n/cm^2 sec

- Occupancy upto 30% *
- Short bunch crossing interval: 25 ns
- High spatial resolution, good pattern recognition: many space points
- Fast and chemically passive active gas: ageing
- Chemically resistant straw materials: straw is basically and electrochemical reactor
- minimal amount of material in front of calorimeter
- Precise and robust mechanical structure: ~100μm/m ~10^{-5}
- Stable temperature: active cooling

* possibly higher occupancy with HI physics

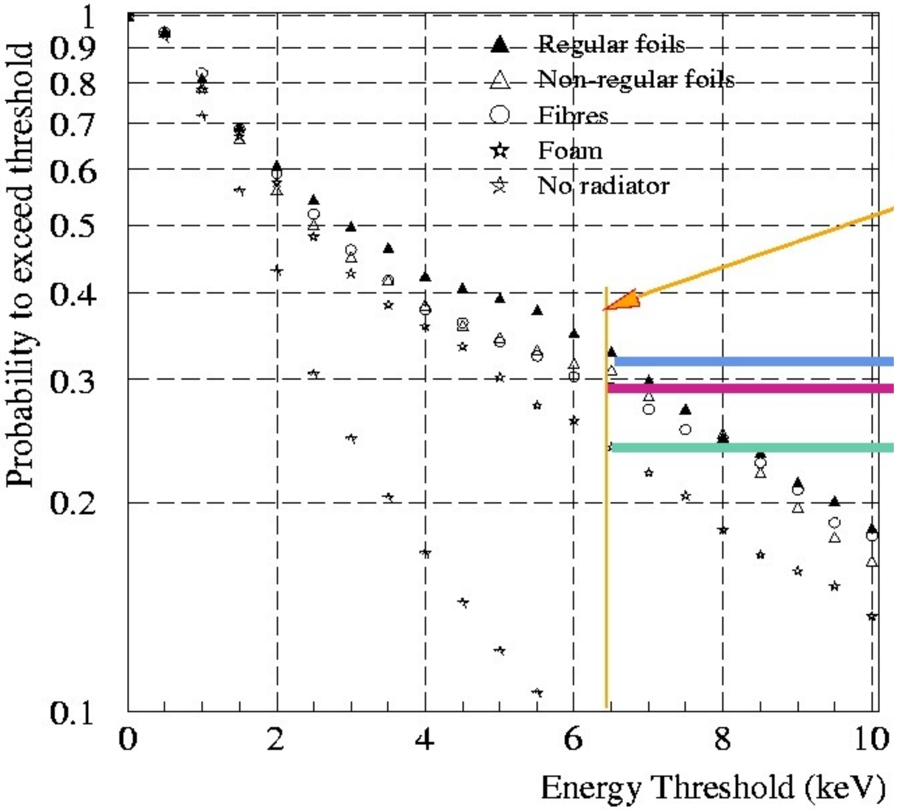
Particle ID using Transition Radiation

- **Transition Radiation: photon emitted by a charged particle when traversing the boundary between materials with different dielectrical constants ($\varepsilon 1 \varepsilon 2$)**
- **Intensity: I ~ γ = E/m**, $\theta \sim 1/\gamma$
  - → Identification of transition radiation photons used for **particle identification** of particles with momenta between 1 and few 100 GeV



- **Emitted energy ~ ($\varepsilon 1$-$\varepsilon 2$)**
  - → Determines choice of materials with maximum difference of $\varepsilon 1$, $\varepsilon 2$ but photon should not be absorbed!
  - → HEP detectors: gases ($\varepsilon 1$) and light plastics ($\varepsilon 2$), photon energies ~10-30keV
- **Radiator** (production of TR photons)
  - Regular radiators (foils),
  - Irregular radiators (foam, fibers),
  - embedded in a gas volume, e.g. CO_2
- **Detector** (observe TR photon, track particle)
  - → Typically: gas chambers using gas with efficient absorption of photons (Xenon)
  - → Absorbed photon produces much higher signal then MIP (point ionization, higher energy)
- Discriminate electrons from hadrons based on number of HT hits on a track
- Use statistical power of many transitions, many straws crossed

Example for radiator materials

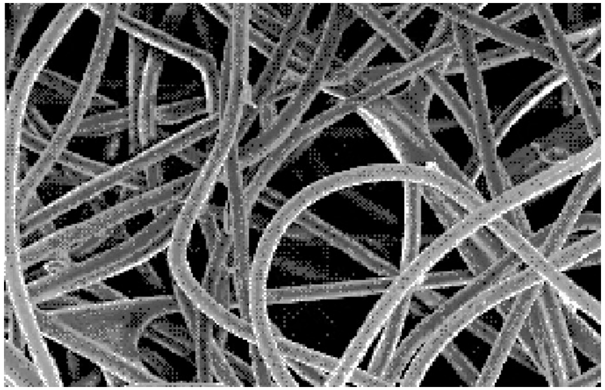


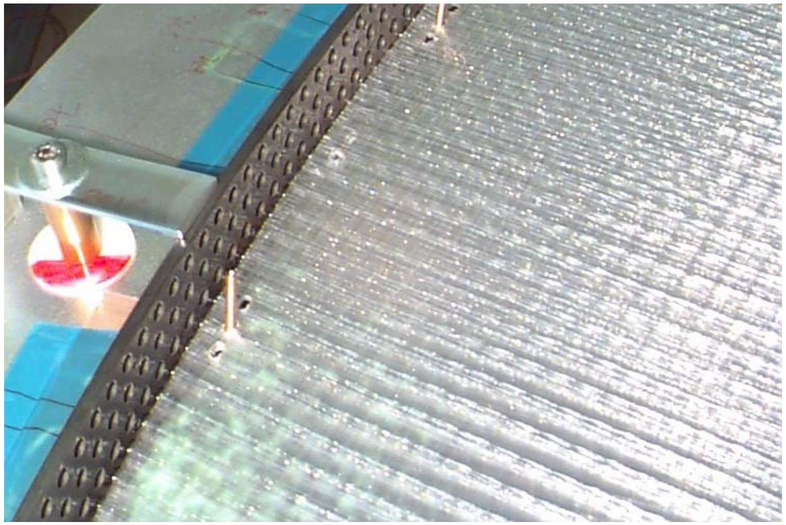
Optimal TR threshold (~6.5 keV)

Regular foils (TRT end-caps)

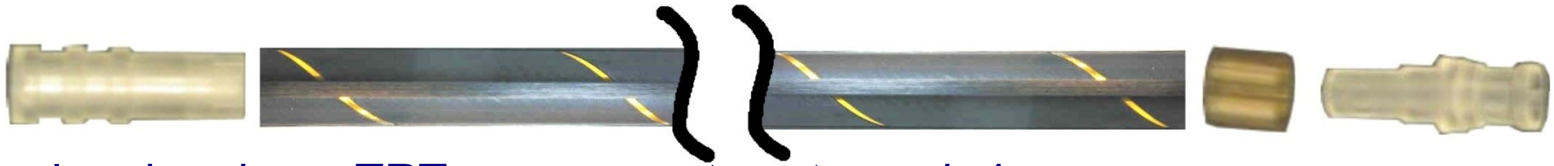
Oriented fibers (TRT barrel)

Foam

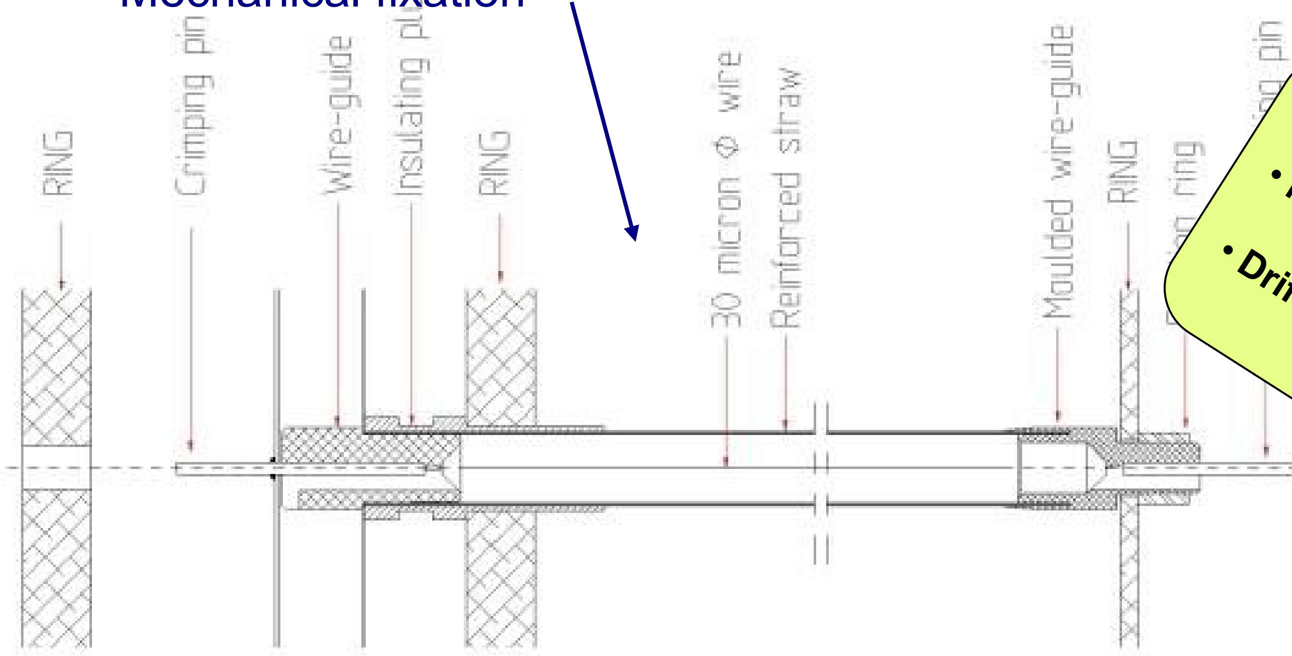




TRT detection elements: straw tubes

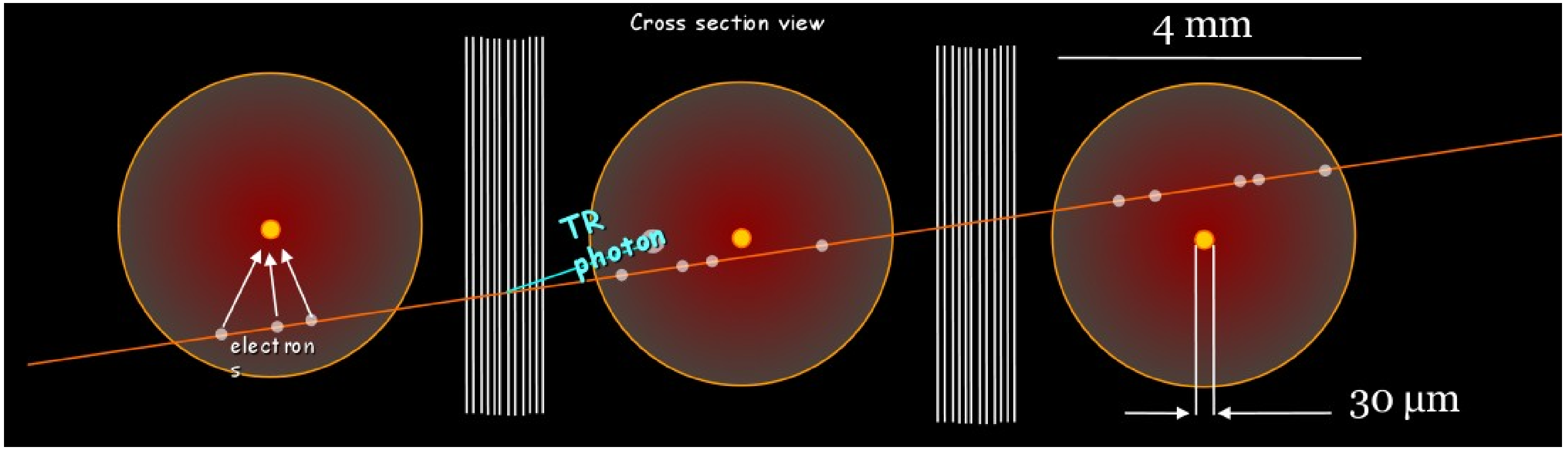


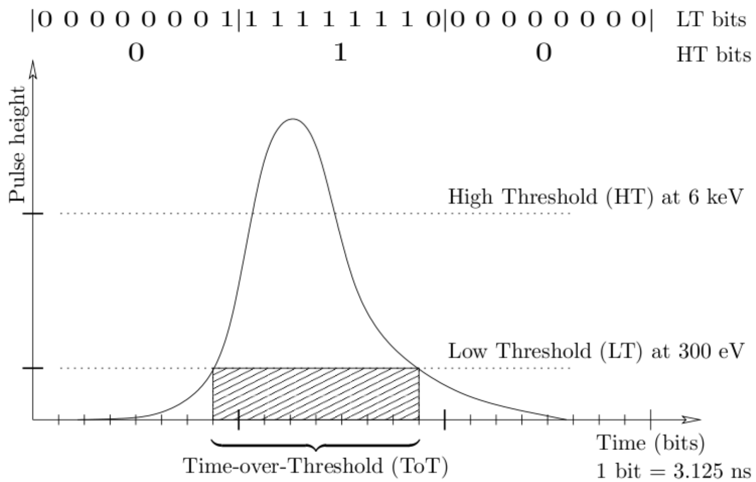
- Barrel and end-cap TRT use same straw type, d=4mm
  - → straw length for end-cap type-A and B: L=39cm
  - → for barrel: L=144cm
  - → each straw is reinforced by four carbon fibers (mechanical stability)
- Straw wall (d=70μm) = cathode @ -1530V
- Wire (d=30μm) gold-plated tungsten = anode @ 0V
- Mechanical fixation



- Gas gain @ working point (1530V): 2.5×10^4
- Maximum electron collection time: 48ns @2T
- Drift time accuracy: ~130μm

Principles of Detection



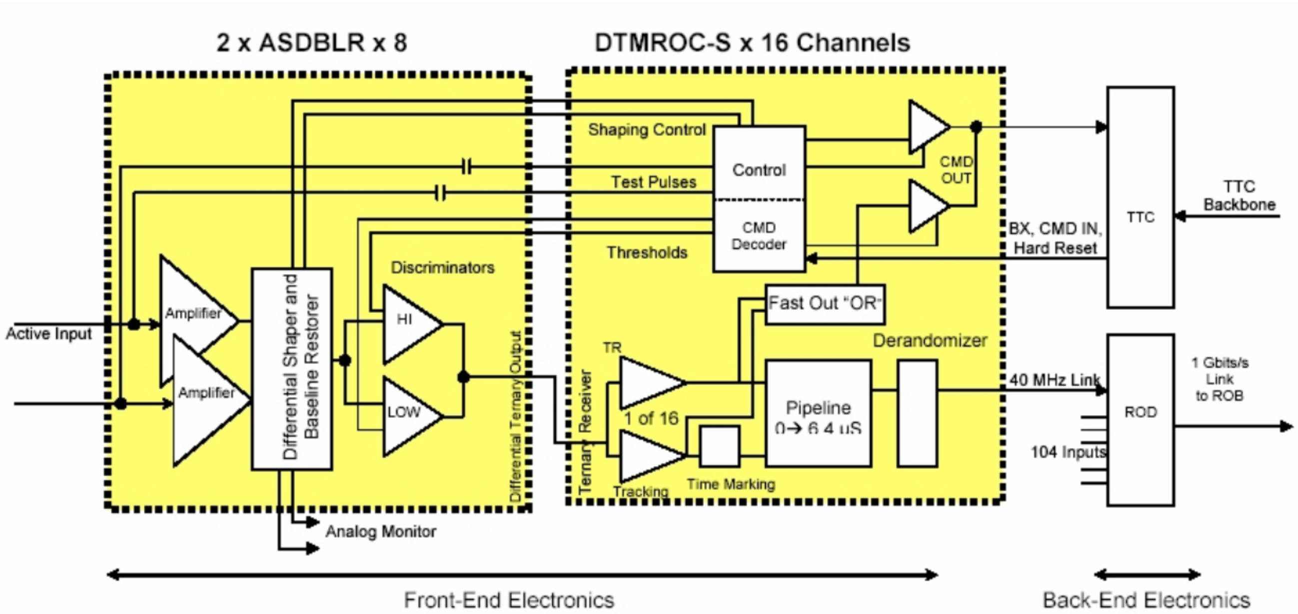


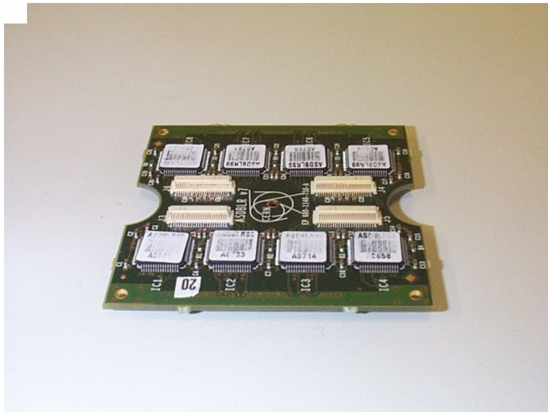
Ionized electrons drift to straw wire to create signal (~several 100 eV)

- — Detect with **Low Threshold (LT)**

- TR photons generate signal ~10keV
  - — Detect with **High Threshold (HT)**
  - — Also with **Time over Threshold (ToT)**
- Readout granularity: **3.12ns**
  - — 1/8 of 25ns LHC bunch crossing (BC)
  - — Readout 3 BCs / trigger

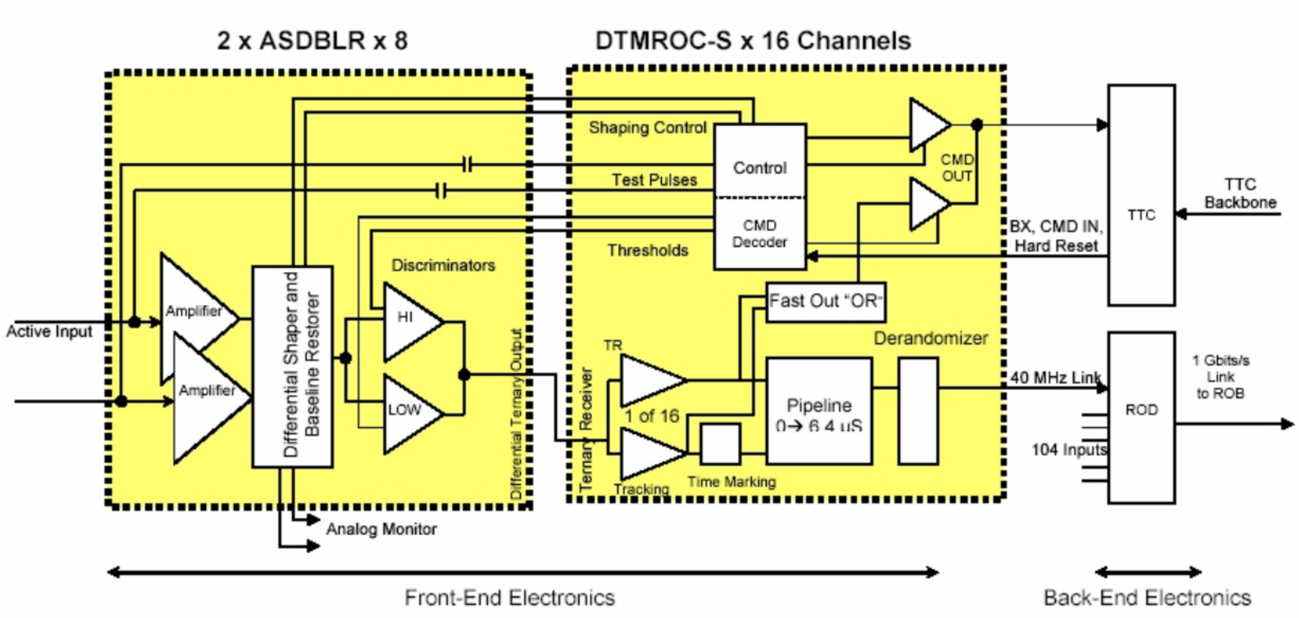
Front End Electronics





- Amplifier, shaper, discriminator, baseline restorer (**ASDBLR)**
- — Analog chip, receives input from **8 channels**
- 2 discriminators, for **low and high thresholds**
- — **Ternary output to DTMROC**

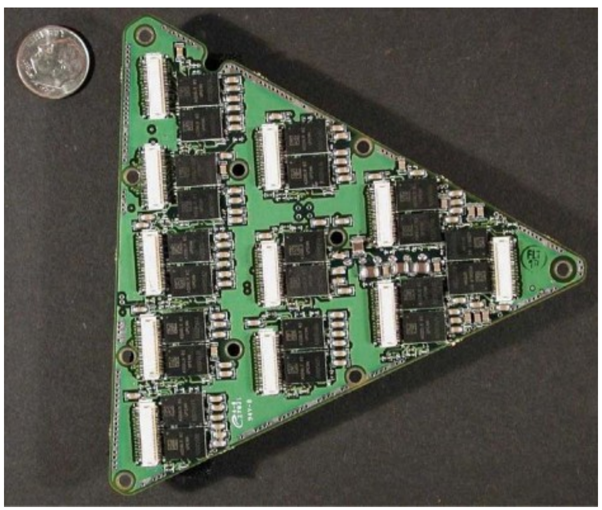
Front End Electronics cont.



- Digital Time Measurement Readout Chip (**DTMROC)**
  - Digital chip, receives input from 2 ASDBLRs (**16 channels)**
- **88kHz max readout rate**
- Key registers **triplicated to minimize** single event upset (SEU) impact
- FastOR output used to generate **trigger** (more later)
- **Temperature and voltage (analog**
- and digital) **readback**
  - Useful for tuning operating voltages,
  - monitoring during runs
- **Test pulse injection at ASDBLR input**

Front End Electronics cont.

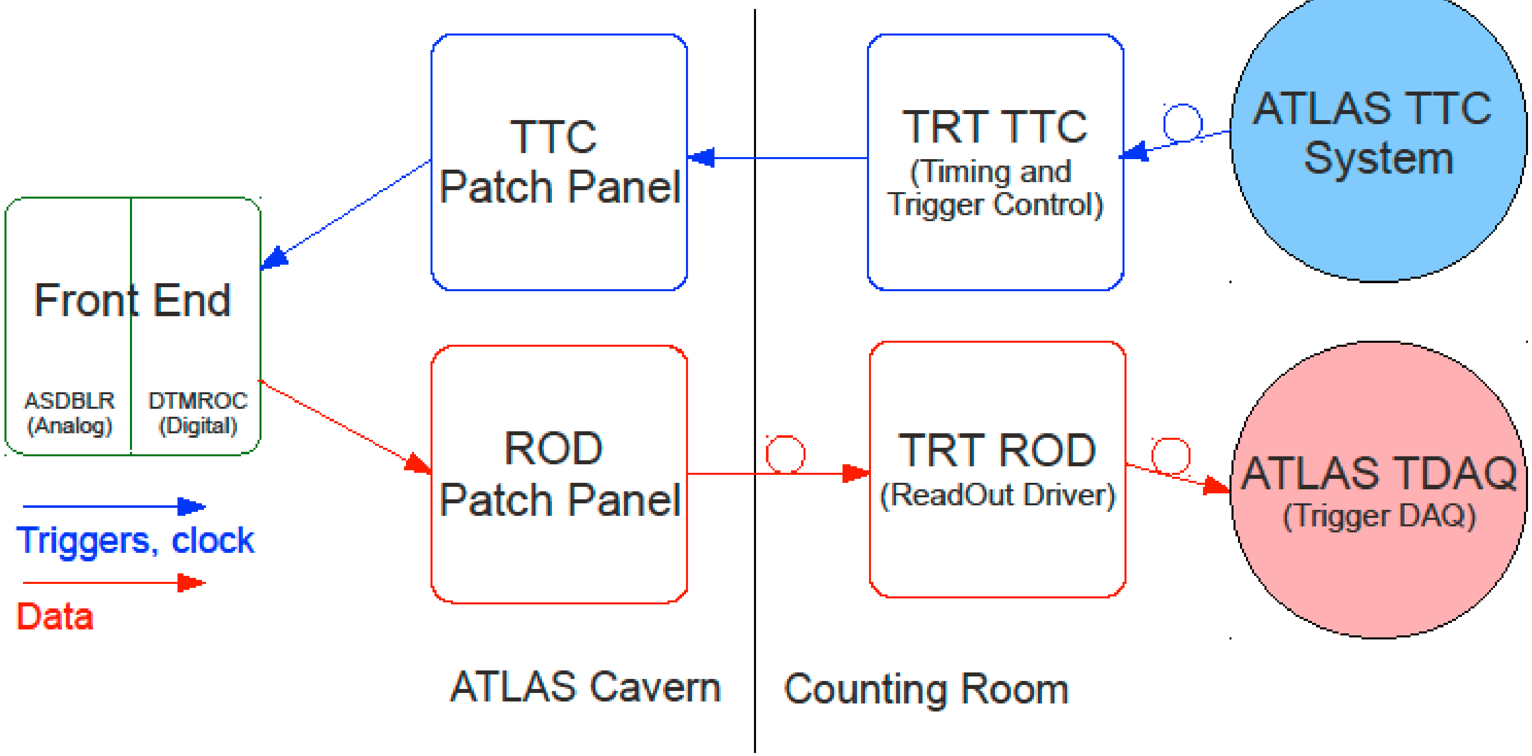
- **Barrel:** analog and digital chips are mounted on opposite sides of the same PCB
  - Analog and digital grounds coupled by distributed low value resistors
- **Endcaps:** analog and digital chips mounted on separate PCBs
- Analog (— + 3V) and digital (2.4V) powered separately



Barrel ASDBLRs

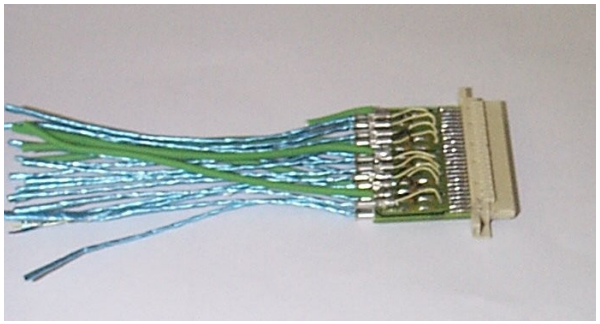
Endcap DTMROCs

(Simplified) Readout Overview



- ROD granularity chosen for L2 trigger:
  - 1/32 in ϕ for barrel, ½ of 1/32 in ϕ for endcaps

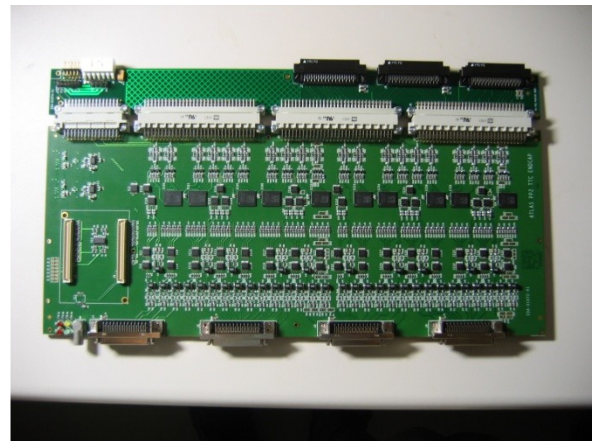
Some pictures



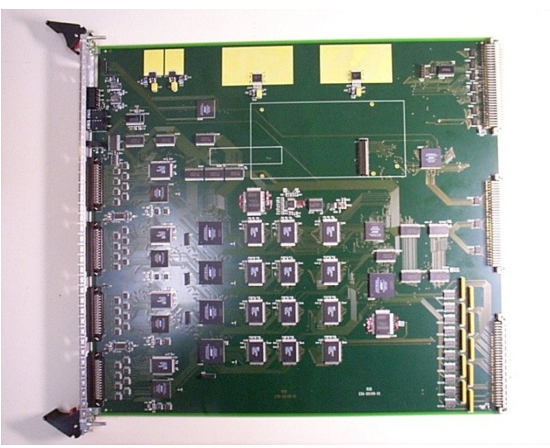
Miniature shielded TWP

(standardized at CERN store)

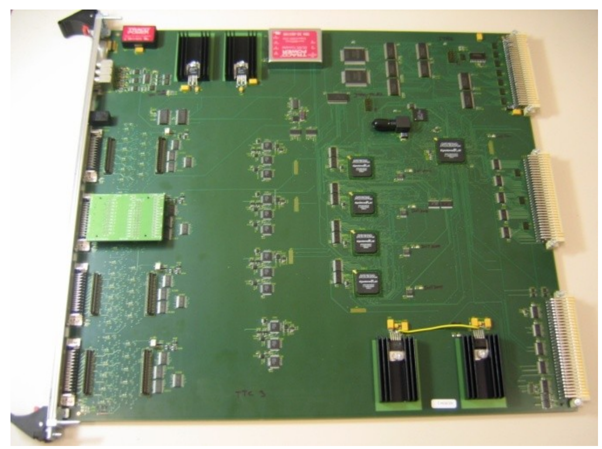
Now also used in nuclear power plants for monitoring



TRT TTC patch panel with active and passive cable equalizers

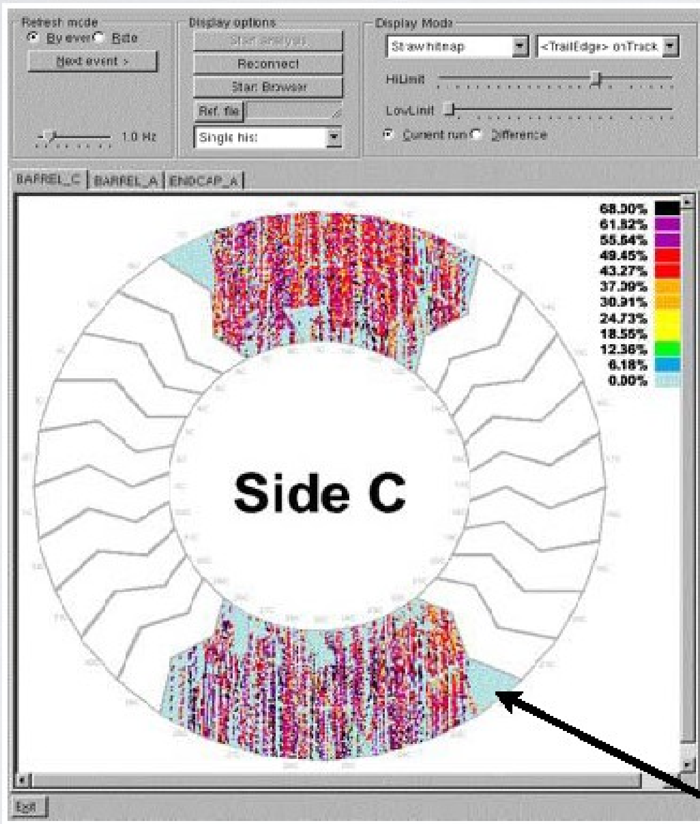


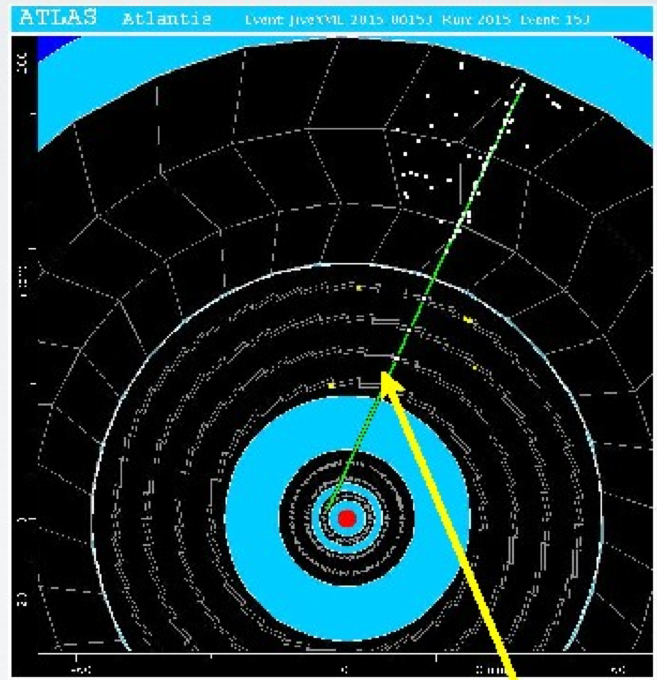
TRT ROD 2003, 1664 straws, 5Gb/s input, 1Gb/s output, VME control



Production TRT TTC with 40 independent links; serving 2/32 of detector side

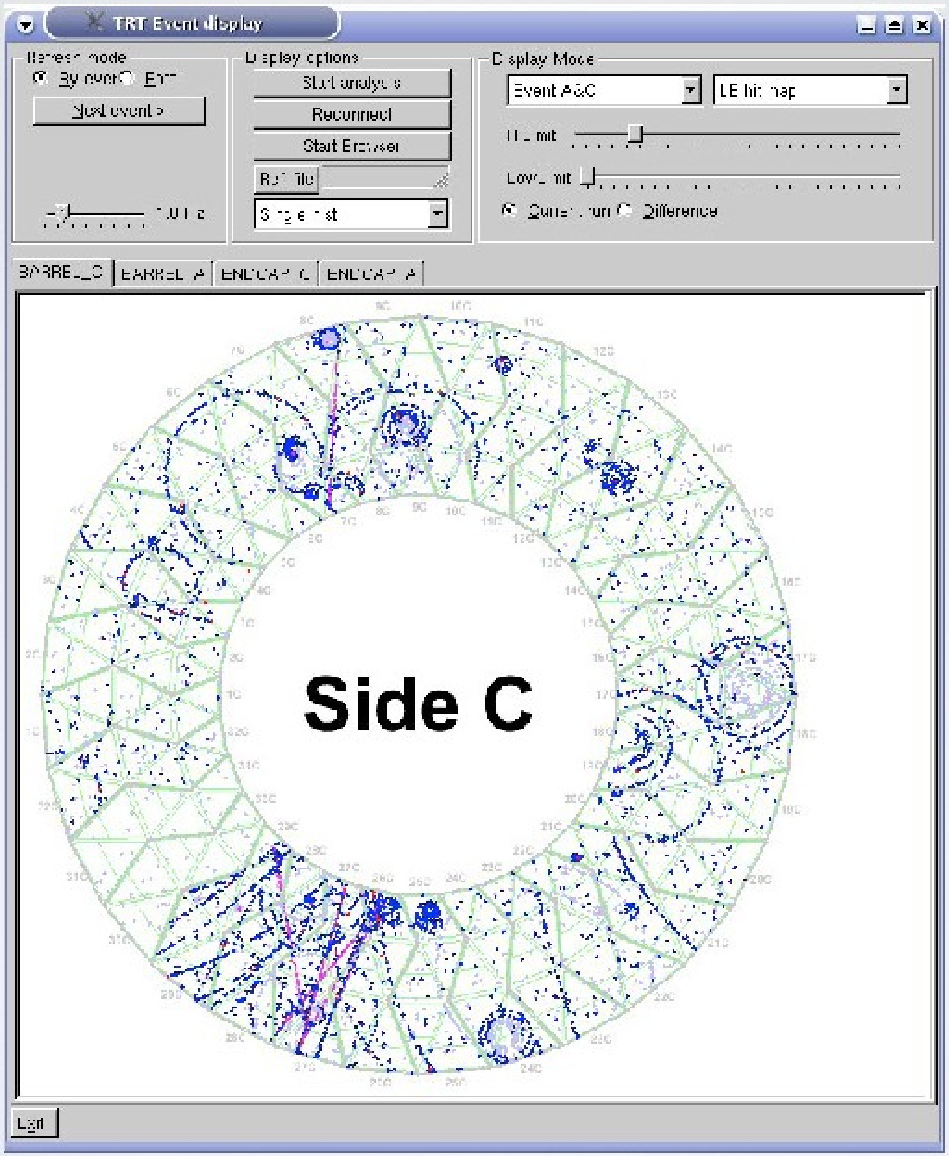
FIRST TRACKS IN THE TRT



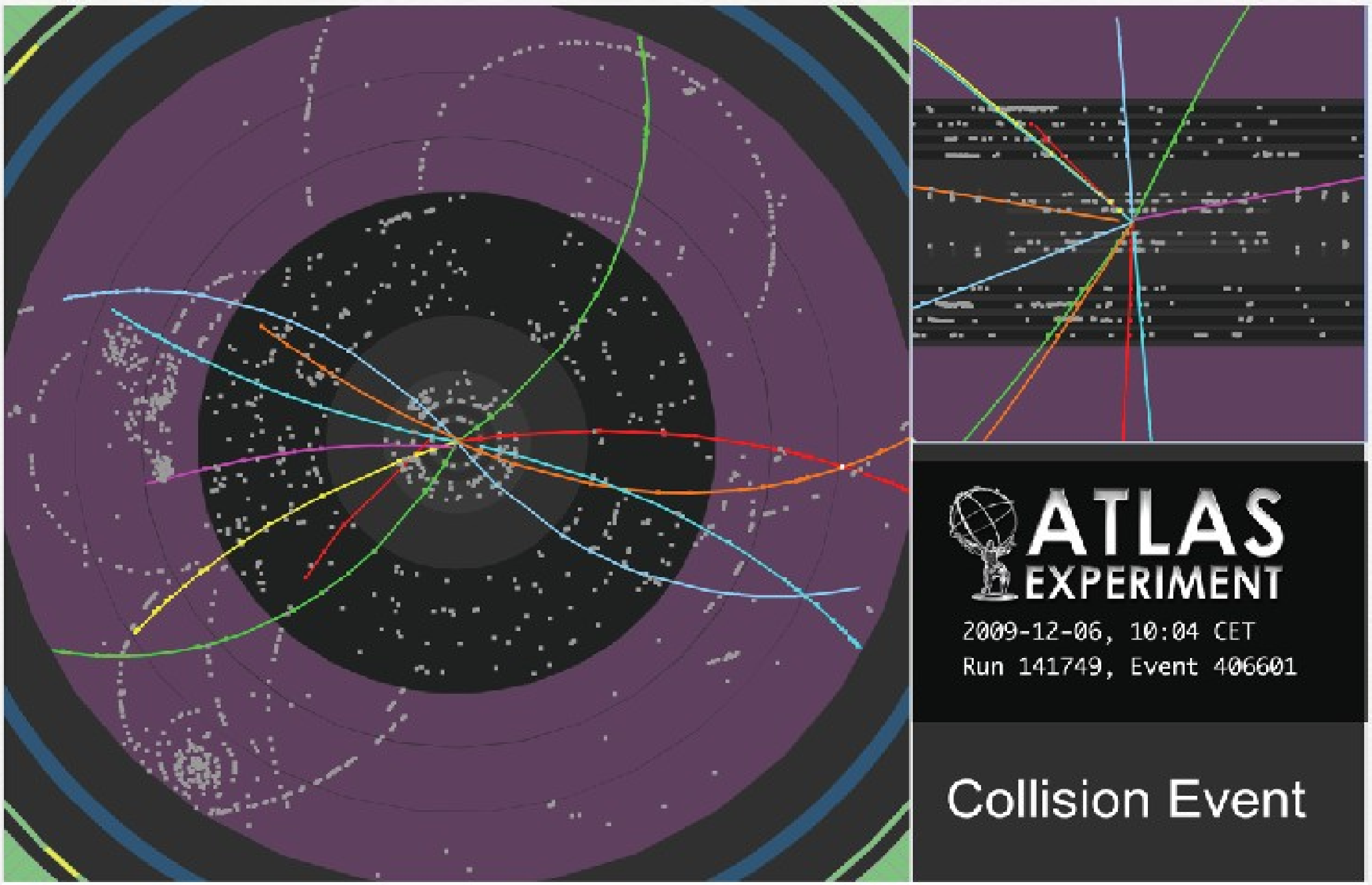


First Track Seen in Tracker
Many more followed

SINGLE BEAM EVENT



STABLE BEAMS



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

W candidate, TR hits in red (positron)