"System Aspects of (Gaseous) Tracking Detectors…

… or what can we learn (have we learnt) from a LHC Detector?

[CMS and ALICE]

- Outline
  - Definitions & Terminology
  - Tracking in LHC heavy ion collisions
  - The challenges
  - The *ALICE TPC* and beyond?
- Outlook
  - A TPC for a Linear Collider
  - Thoughts and ways to go towards solutions

Definitions & Terms

- 'System'
  - A system, for our case, is the entire instrument built for an experiment or collaboration, to collect, filter, and analyze data (e.g. ALICE, CMS, ALEPH…).
- 'Detector'
  - A detector or subsystem is a component of the 'system' with specific tasks congruent with the other sub-systems.
- 'Optimization'
  - Although specific in its task(s), a detector must not be optimized for highest performance for itself, but rather be 'subordinate' to the global system objectives.

System Aspects & Optimization

- Optimization is: Build to purpose!
  - Compliance with specs, schedule and cost
  - Compatibility (*sociability*) with neighbor detectors (x_o, noise, heat…)
  - Adapting to environment and run conditions
  - Respecting safety regulations and
  - Securing capital investment.
- This requires a coherent, system oriented, execution plan from R&D to commissioning!

Examples

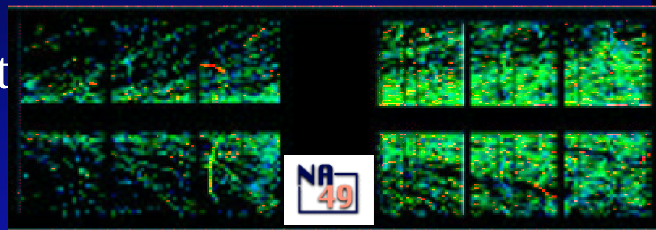
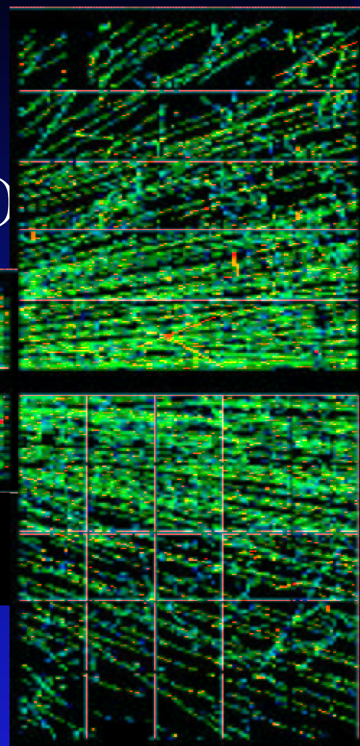
- UA1 & CMS: A coherent *system* concept
  - 'Fail-safe' muon detection with large absorber (comp.)
    - ➡ magnet design and specs
      - ➡ calorimeter design
        - ➡ tracking detector design
- ALICE TPC: A coherent *detector* concept
  - 'Low-mass', low disturbance premise for the measurement of low momenta and particle identification
    - ➡ Field cage material, gas choice
      - ➡ Gas gain
        - ➡ Readout scheme & electronics
          - ➡ Tolerances

Counter Examples

- The U-TMP calorimeter of UA1:
  - Perhaps too ambitious (built to purpose?)
  - Underestimate of technical complexity
  - Failed on cost and schedule issues
- The MSGC tracker of CMS:
  - Overoptimistic laboratory results
  - Nonconformity with real environment
    - sparks from hadronic interactions with substrate
  - Failed on schedule and milestone adherence
  - Or, was it a political issue?

LHC Lesson 1

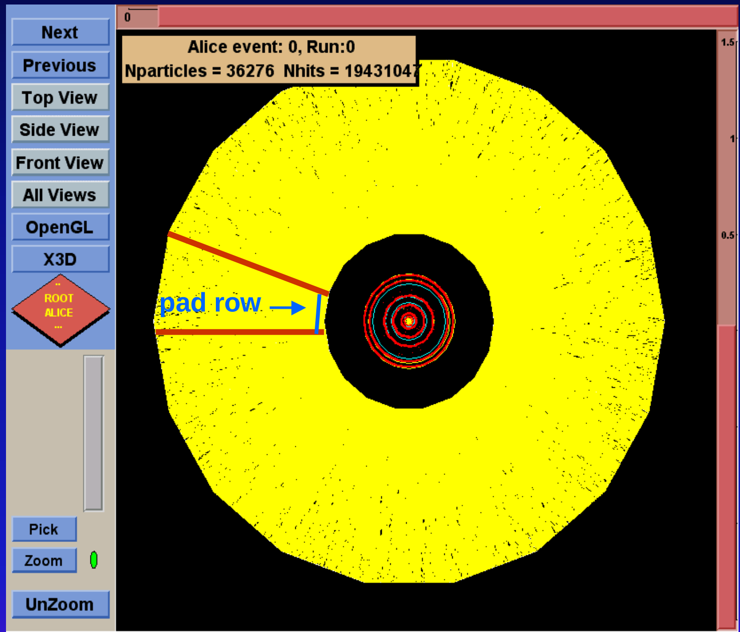
- Unprecedented rates (p-p) & multiplicities (heavy ions)
  - p-p-physics at the picobarn level (want $\mathcal{L}$ high)
  - Pb-Pb-physics at the millibarn to barn level (want $\mathcal{L}$ low)
  - LHC stored beam energy ~ 60 kg of TNT equivalent
- Radiation damage
- Inaccessibility of apparatus
- Duration and size of projects
- Particularly difficult transition for LEP "descendants"

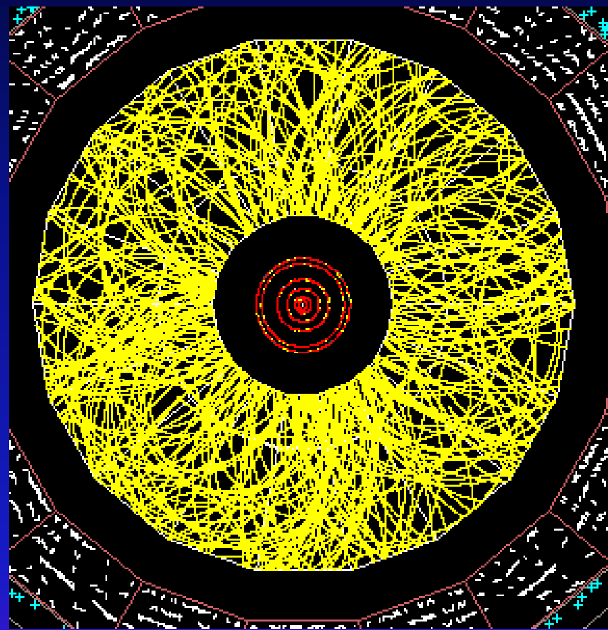
NA49: Pb-Pb
158 GeV/nucleon

Lessons from LHC Pb-Pb

- The principal challenge is track density
  - $dN_{ch}/d\eta \sim 8000^{*)}$ (for $|\eta| \leq 1$) --> ~24'000 primary particles (charged + neutral) + ~ 50% secondaries --> ~ 2 x10^7 hits



Full projection into readout plane

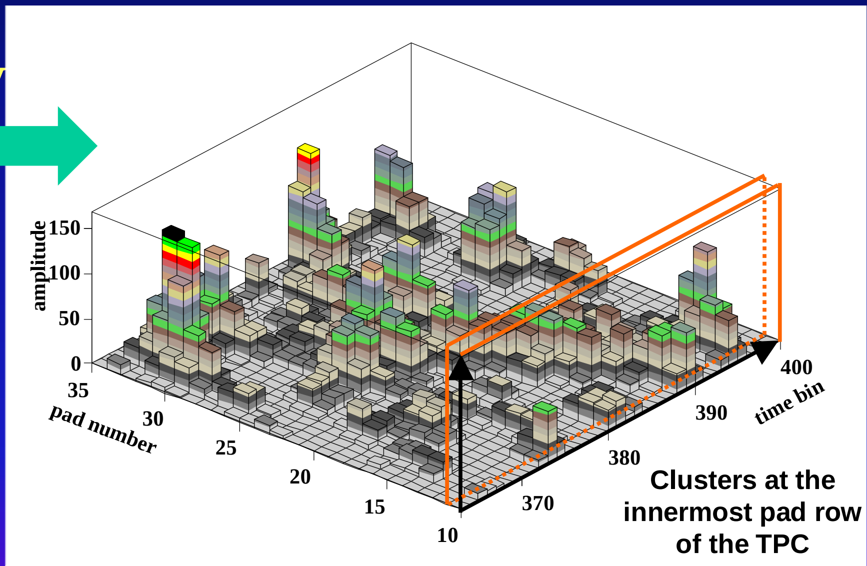


Slice of 2° in θ

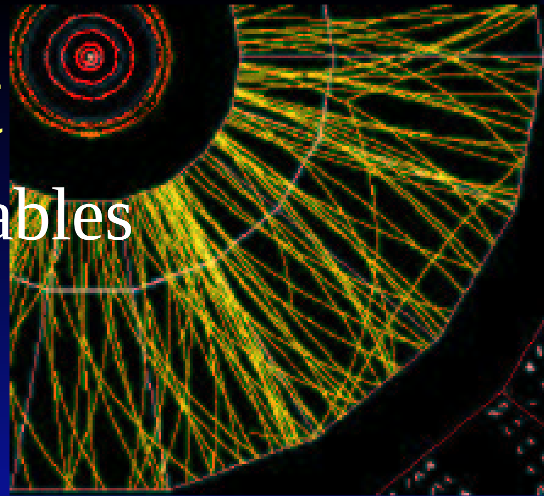
*) very conservative assumption

Consequence: Occupancy → TPC

- Why a TPC?
  - For coping with high instantaneous rates, TPC is best suited, for it delivers space points, and many of them (redundancy).
  - TPCs are relatively massless --> strong reduction in secondary particle production (background)
- We define Occupancy
  - N_{above}/N_{all} in pad-time-space
- For ALICE TPC:
  - Innermost pad row: ≤ 50%
  - Outermost pad row: ≤ 17%
  - Average occupancy: 25%



The Role of Tracking in HI Physics

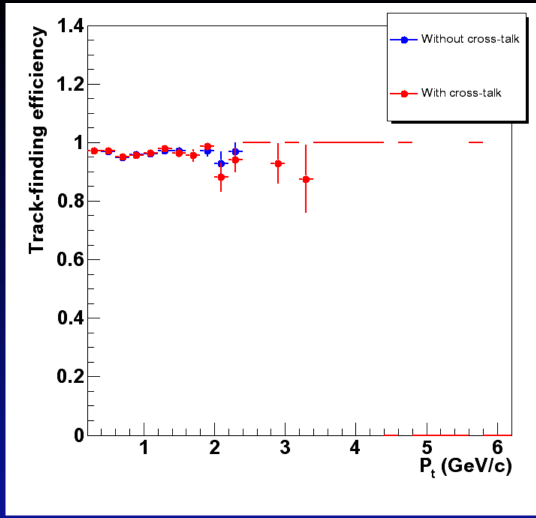


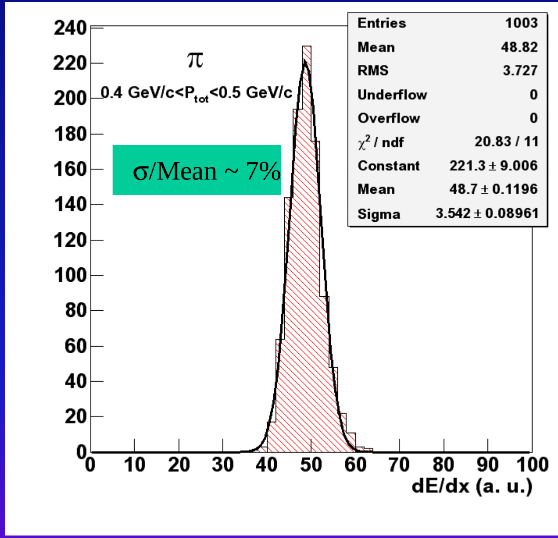
- Momentum measurement
  - For hadronic and leptonic observables $100\ \text{MeV/c} < p_t < 10\ \text{GeV/c}^{*)}$
- Particle identification
  - Separation of hadrons and identification of elec.
- Tracking
  - Matching with inner and outer trackers
  - High track finding efficiency

*) limited by magnetic field strength

Performance Goals: eg. ALICE-TPC

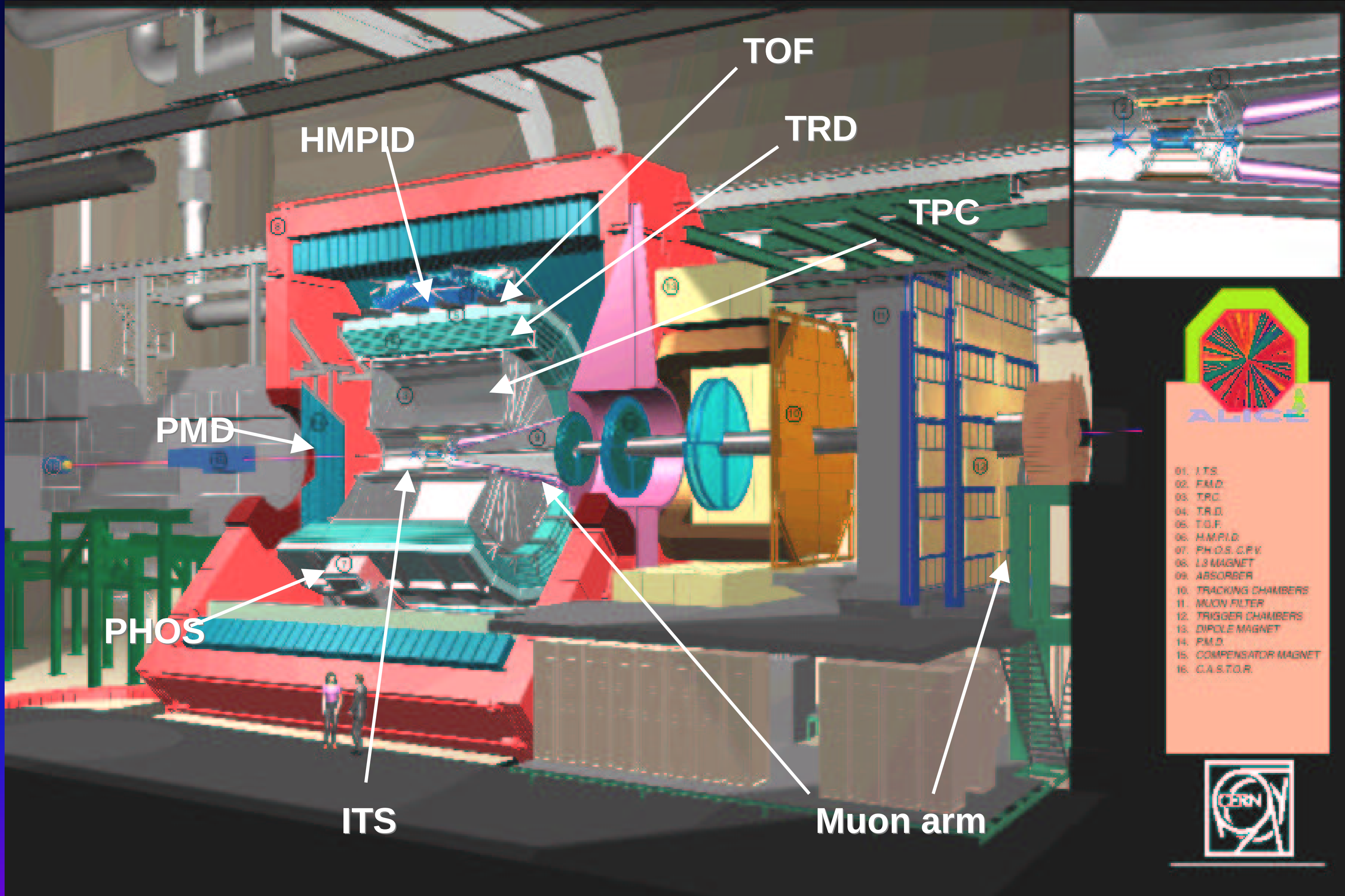
- Track finding efficiency:
  - > 95% for p_t > 100 MeV/c
- Momentum resolution:
  - dp_t/p_t < 1.2 - 1.5% for MIP





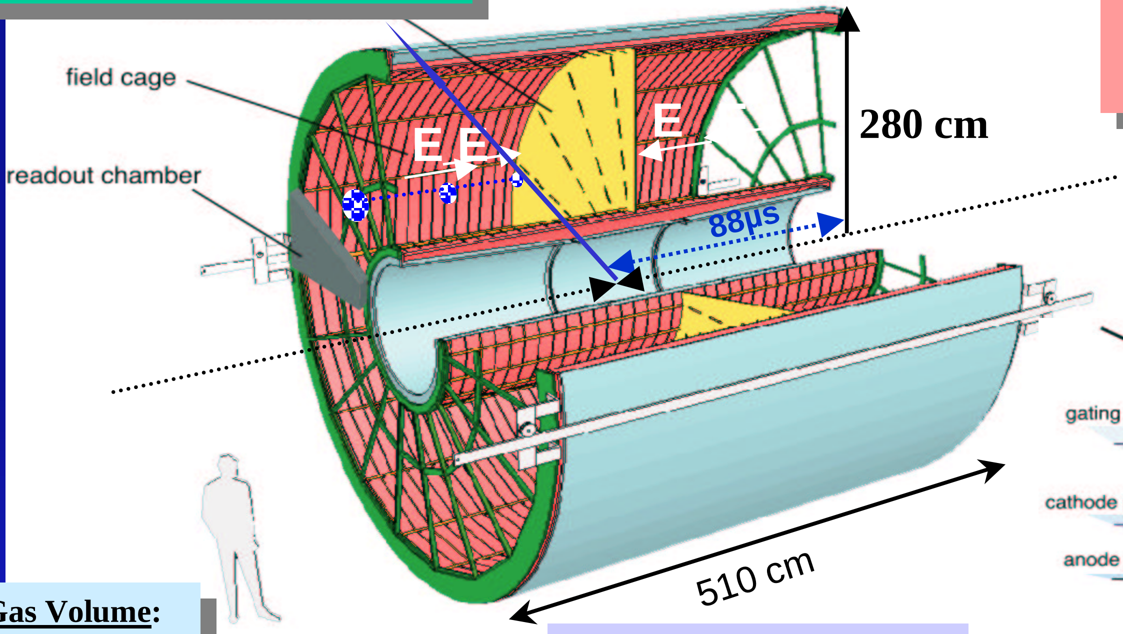
- dE/dx-resolution:
  - < 10% (at high density)
- Rate capability:
  - 200 Hz central Pb-Pb ($\mathcal{L} = 10^{27}$ cm^{-2} s^{-1})
  - 1 kHz p-p ($\mathcal{L} = 3 \times 10^{30}$ cm^{-2} s^{-1})

The ALICE Detector System



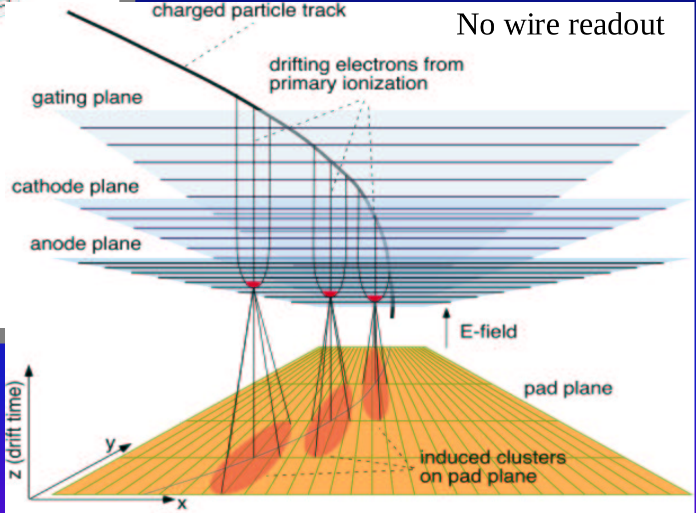
ALICE TPC: Layout

Readout plane segmentation
18 trapezoidal sectors
each covering 20 degrees in azimuth



Large Data Volume

- **570 132 (pads) x 500 (time bins)**
- **356 Mbytes / event**
- **Pb – Pb (@200 Hz) ➔ 71 Gbyte/s**
- **p-p (@1KHz) ➔ 356 Gbyte/s**

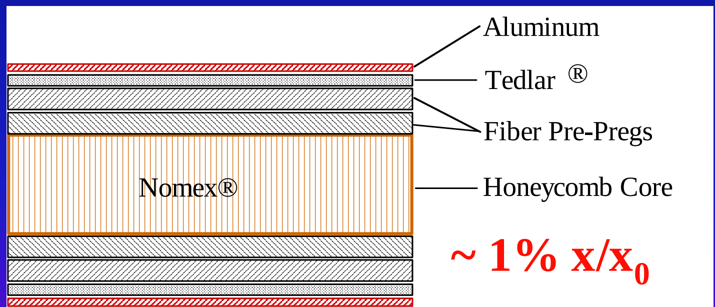


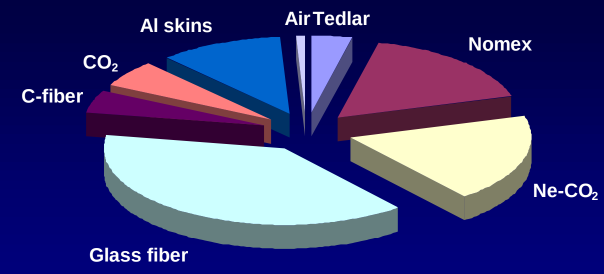
Gas Volume:
88 m^3
Drift gas:
Ne-CO_2 (90-10)

"Russian Doll" principle for detector "containment"

Challenge: Low Mass

- Needed for
  - (e-identification/TRD)
  - Minimizing multiple scattering
- Choose <u>composite</u> material for both the inner field cage and containment structure:





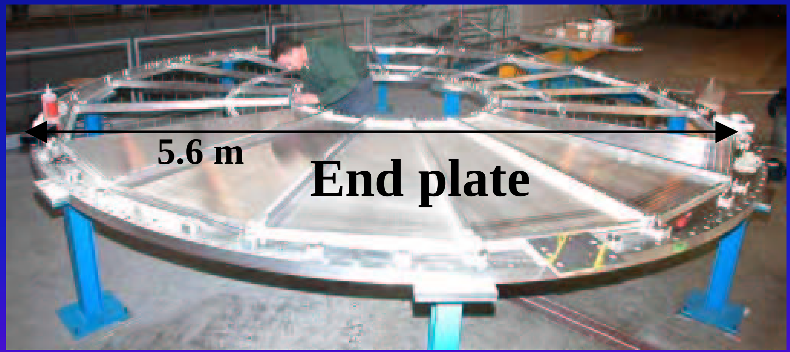
Total x/x_0 ~ 3% (η = 0)

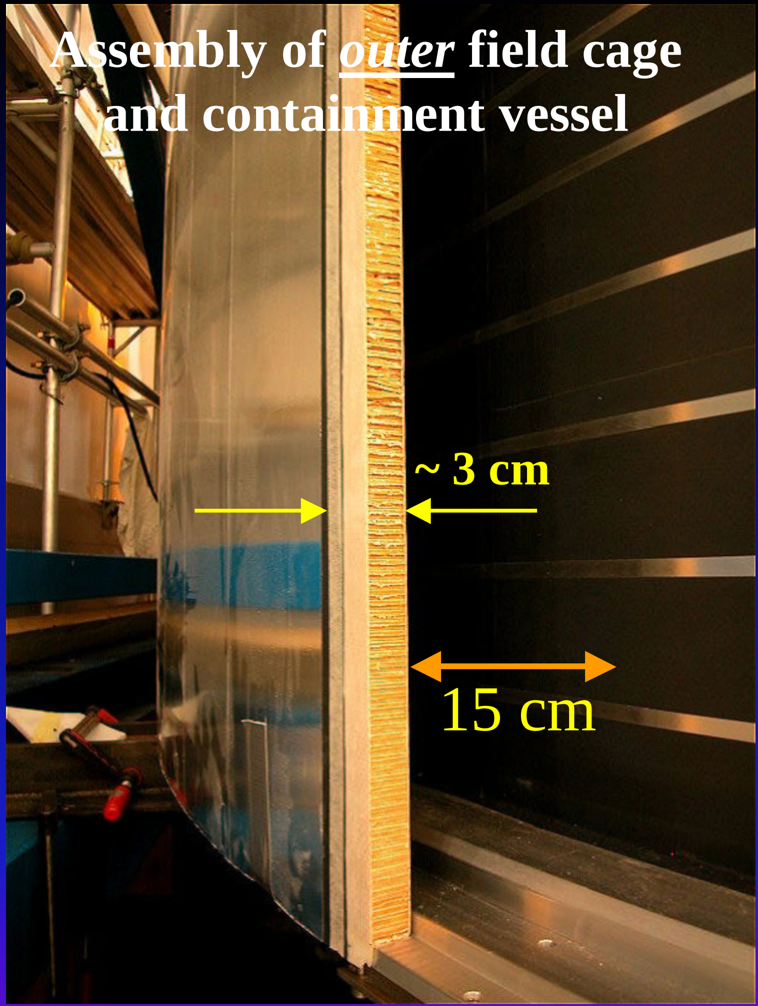
- Choose <u>neon</u> instead of argon as main gas component

Field Cage: Design Objectives

- Ensure:
  - Stable gas gain: $> 10^4$
  - Drift field: 400 V/cm with $E_r/E_z \leq 10^{-4}$
  - Temperature stability: $\Delta T \leq 0.1$ °C
  - Drift gas purity: < 5 ppm O_2 and 10 ppm H_2O
- Provide high mechanical accuracy for…
  - Central electrode: 250 µm (planarity and position)
  - Readout plane: 250 µm (idem)
- High structural integrity at low mass:
  - Use composite honeycomb structures: Nomex, Tedlar, fiber matrices
- Operate safely at very high voltages (100kV)
  - Use double wall insulation (containment)

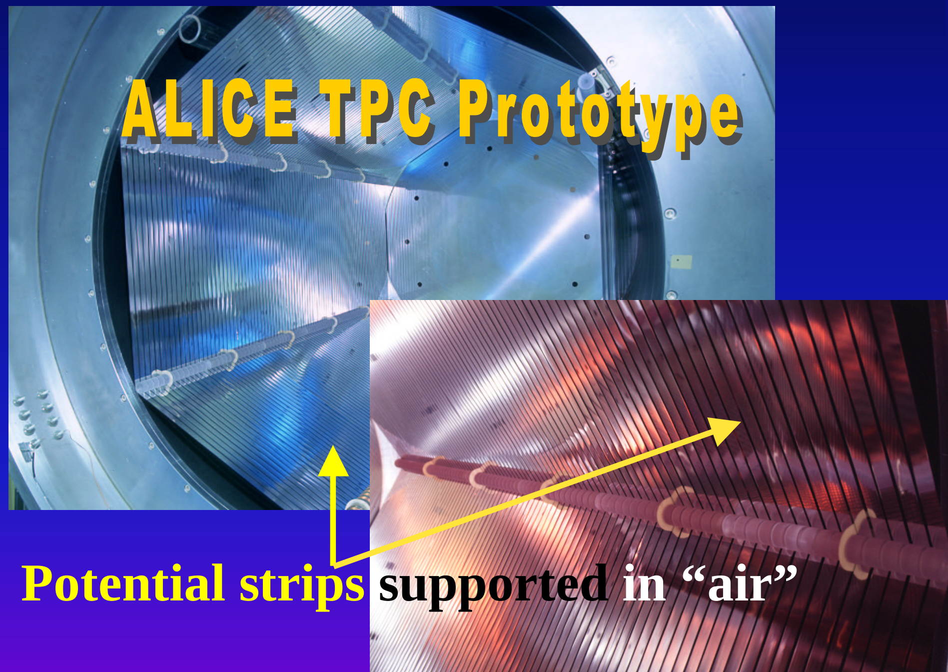
Field Cage: Components





Challenge: E-Field Uniformity

- Provide E-field homogeneity of $dE_r/dE_z \leq 10^{-4}$, to match intrinsic TPC space-point resolution (300-2000 μm):
  - Rods even out irregularities on cylinder surfaces (mm!).
  - Suspended strips avoid surface charges (NA49).
  - Central electrode vs readout plane alignment 250 μm/2500 mm!
  - Severe constraints for large structures!



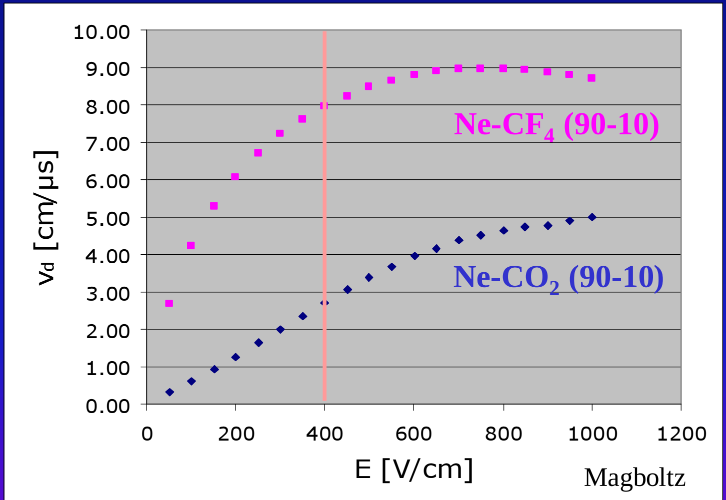
Challenge: Gas

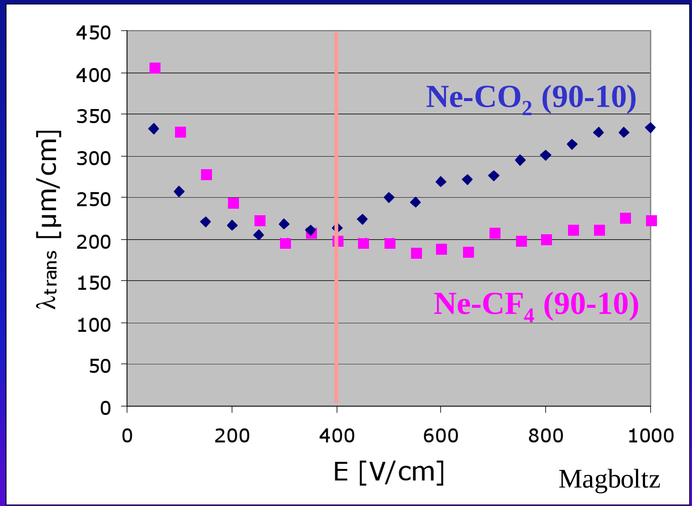
- Options:

Courtesy Rob Veenhof: "Choosing a gas mixture for the ALICE TPC"
ALICE Internal Note

	Helium	[illegible]	[illegible]	[illegible] $_2$	[illegible] $_4$
ρ [g/l]	[illegible]	[illegible]	[illegible]	[illegible]	9
X_0 [[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	8	[illegible]	[illegible]
[illegible]		4	[illegible]		

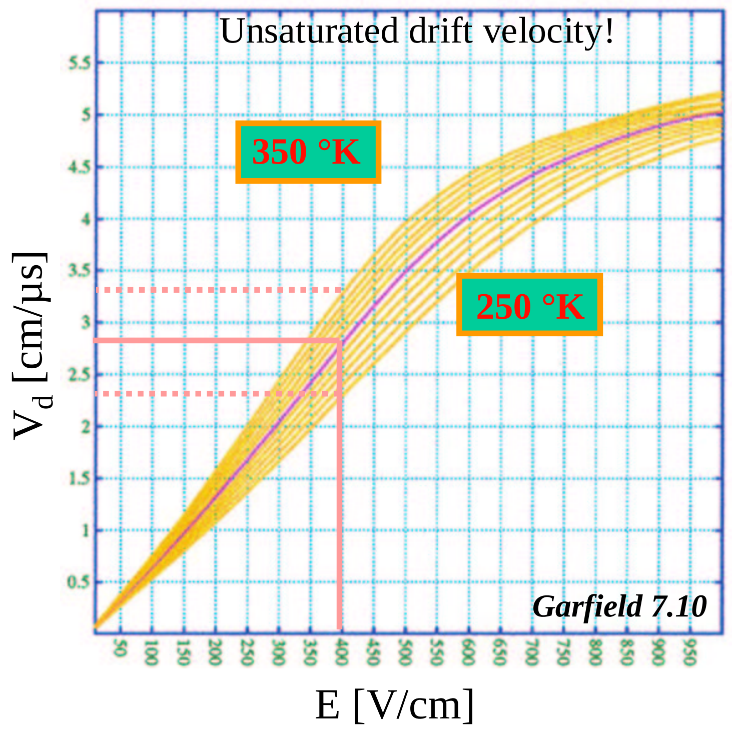
- Choose Ne plus CO_2 as quencher:





Gas Choice: Consequences

- $Ne\text{-}CO_2$ is very sensitive to <u>temperature</u>, pressure and mixture variations:



Ex.: Temperature sensitivity:

$$\frac{3.25 - 2.25\ cm/\mu s}{2.83\ cm/\mu s} / 100\ °K = \underline{0.35\%/°K}$$

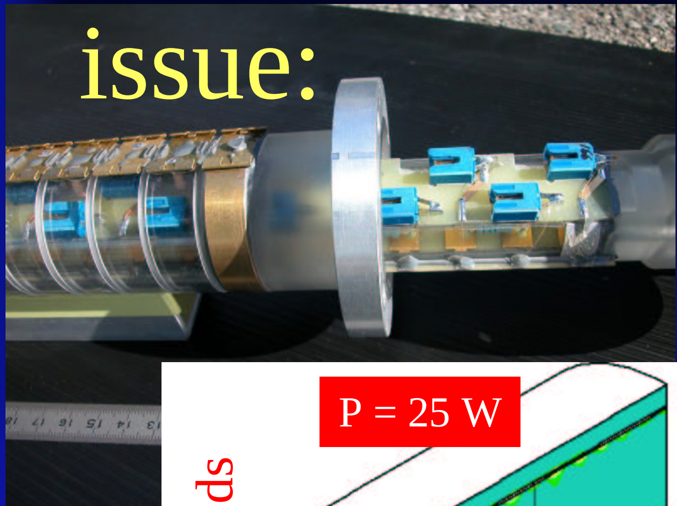
To limit track distortions to the intrinsic resolution of the detector (~ 1000 µm)

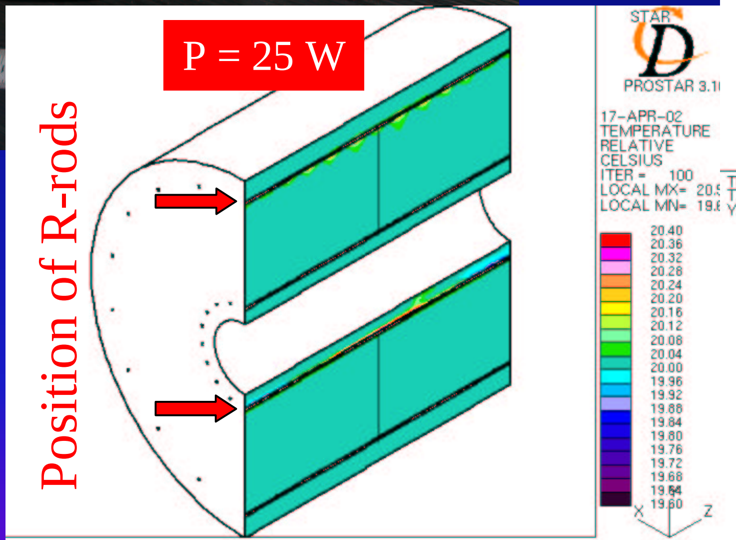
ΔT must not exceed 0.1 °K

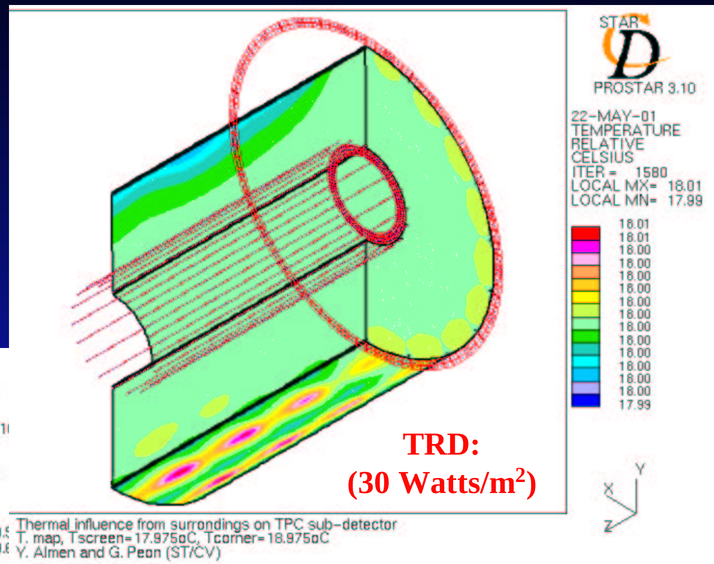
Courtesy Rob Veenhof: "Choosing a gas mixture for the ALICE TPC" ALICE Internal Note

TPC: Thermal Isolation

- Complex integration and operation issue:



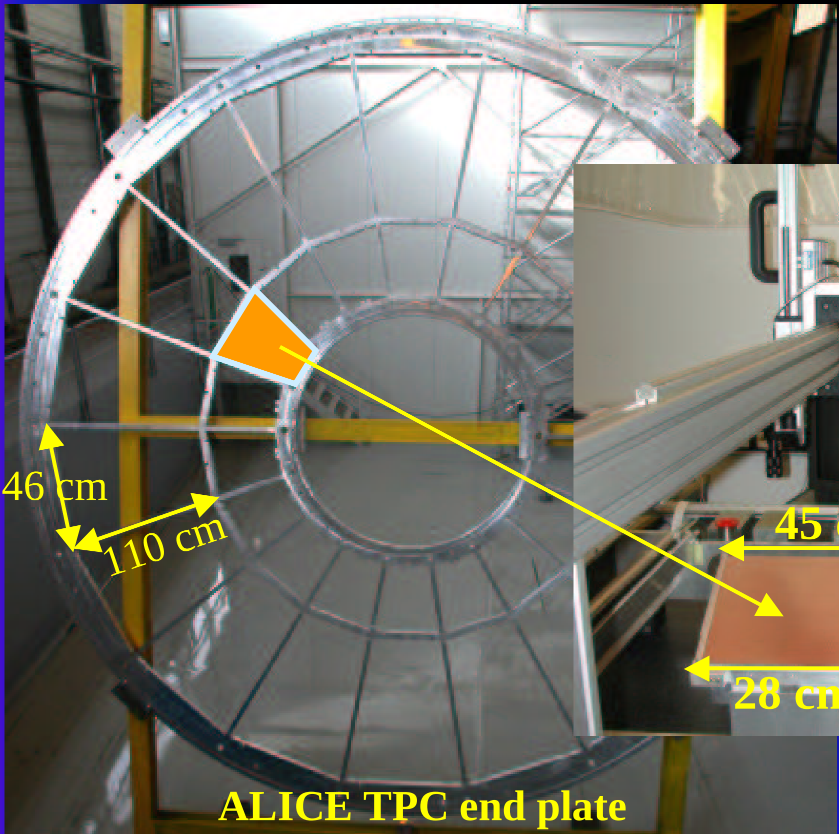


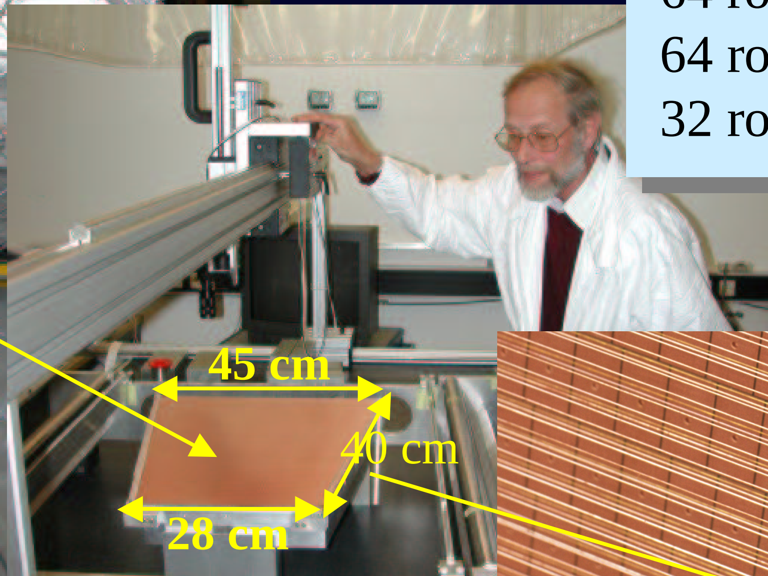


Must protect TPC from external heat sources (ITS, TRD)

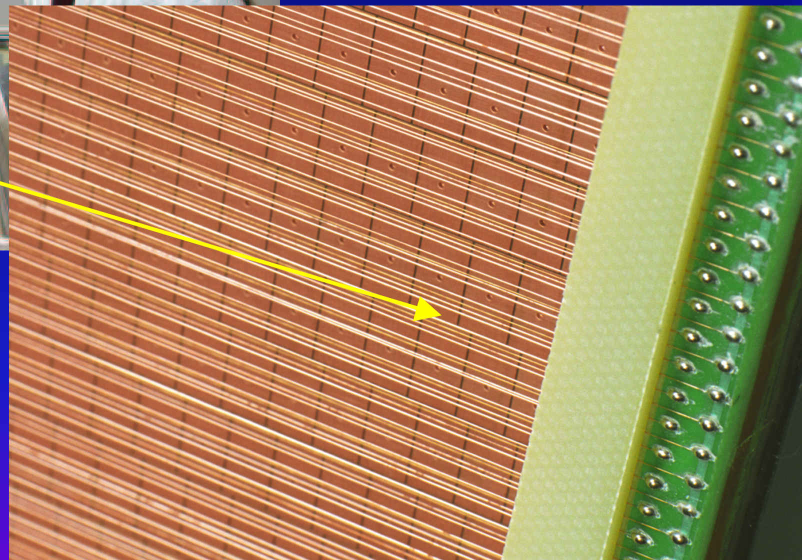
Must cool the resistive voltage divider chain (4 x 8 Watts)

Readout Chambers





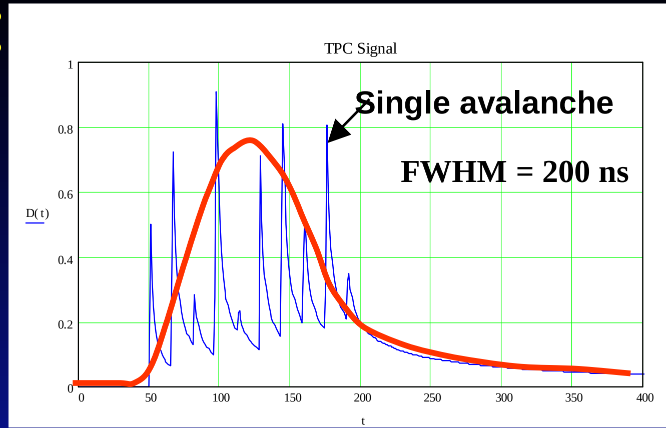
From inside out:
64 rows with 4 x 7.5 mm^2
64 rows with 6 x 10 mm^2
32 rows with 6 x 15 mm^2



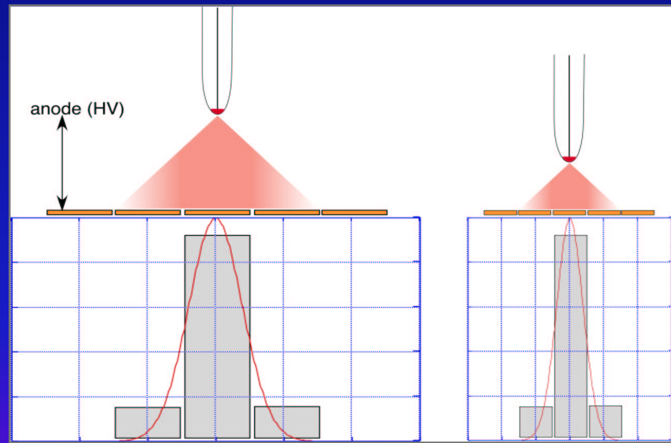
Anode wire plane *<u>without</u>* field wires

Challenge: Readout in HI Tracking

- z-coordinate (time direction):
  - smaller time bins, but…
  - signal/noise gets critical for τ_{FWHM} < 200 ns
  - temporal signal is diffusion limited!

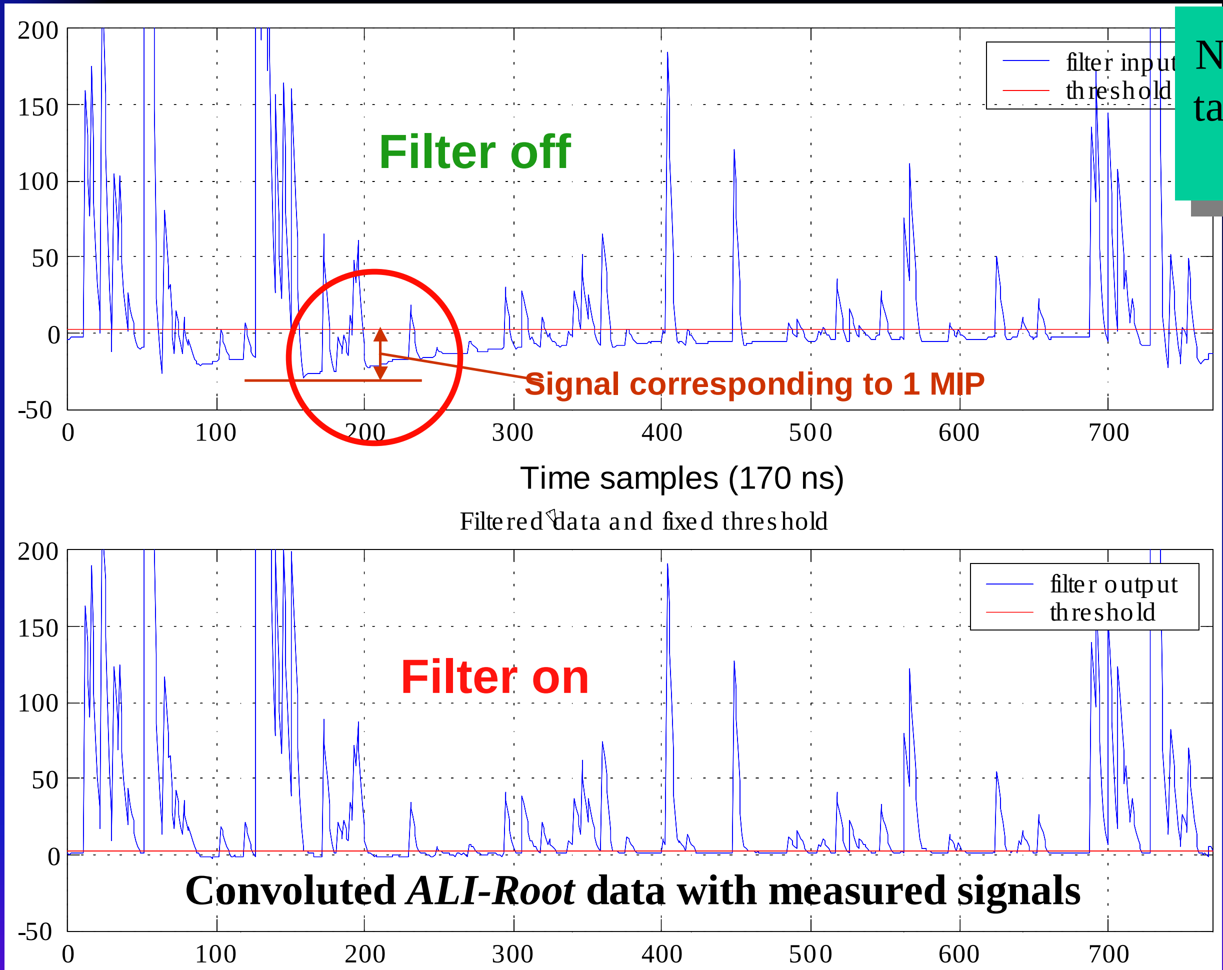


- r-ϕ-direction (pad direction):
  - Smaller pads, but…
  - No. of channels increases --> cost!
  - Sense wire HV to ground gets critical.
  - Resolution is limited by diffusion, fluctuations and angular effects.



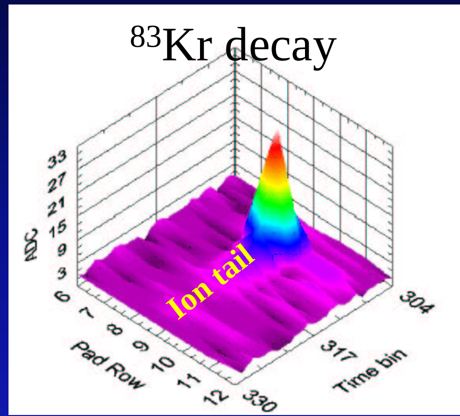
- Solution:
  - Choose the pad-time area that still yields reasonable signal (S/N > 20).
  - For a given pad area, optimize the aspect ratio
  - Minimize diffusion --> high drift fields.

Filter: The Ion Tail Problem

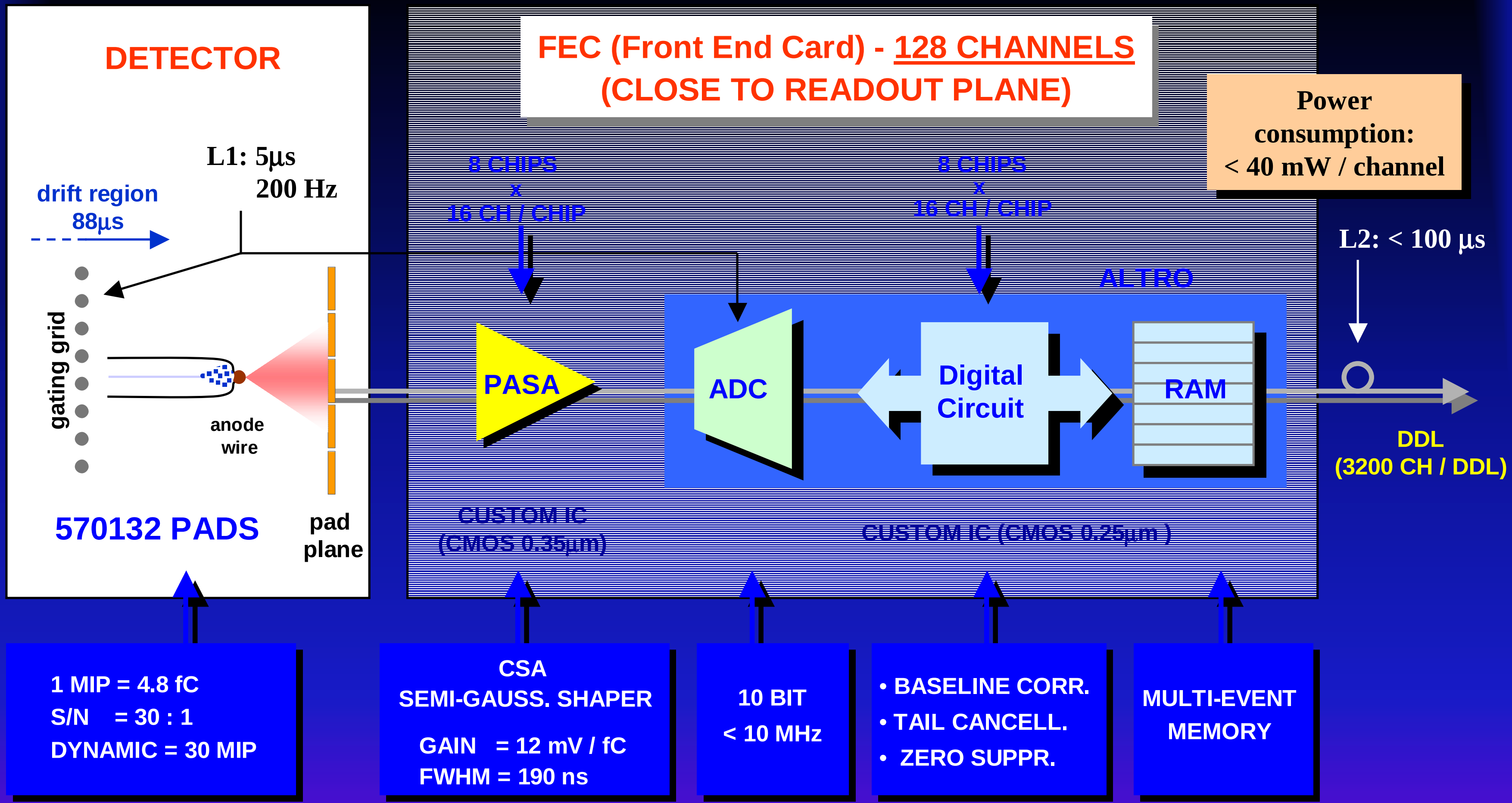


Convoluted *ALI-Root* data with measured signals

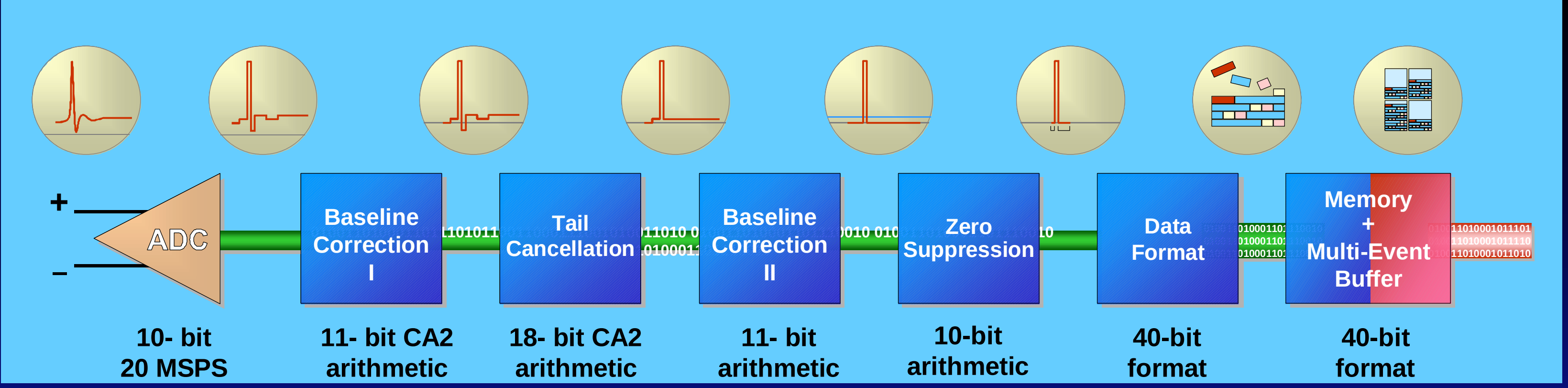
Need efficient algorithm for tail cancellation and baseline correction



TPC Readout: FEC



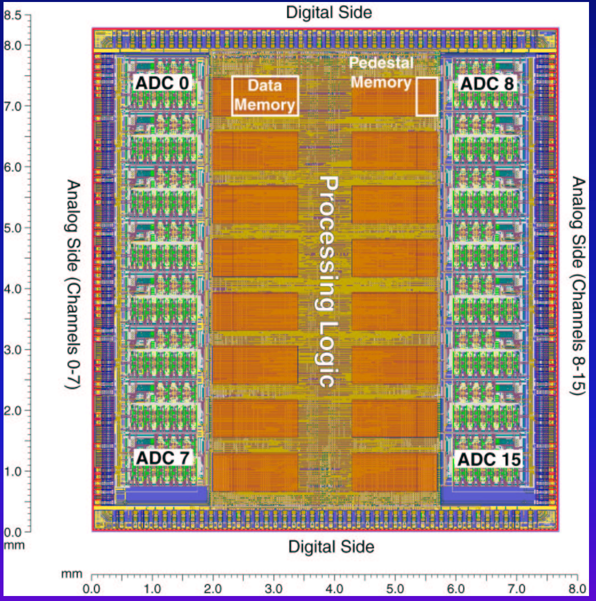
ALICE TPC Readout Chip (ALTRO)



- MAX SAMPLING CLOCK 40 MHz
- MAX READOUT CLOCK 60 MHz

16-CH Signal Digitizer and Processor

- HCMOS7 0.25 µm (ST)
- Area: 64 mm²
- Power: 16 mW/ch

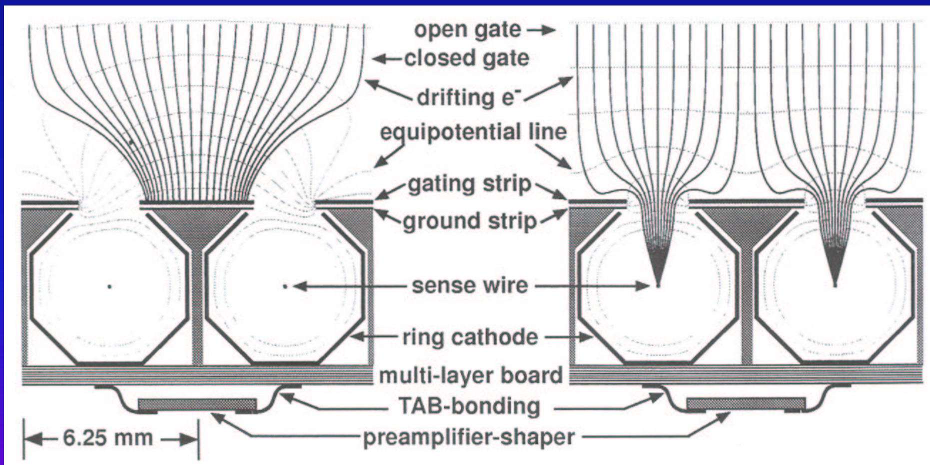


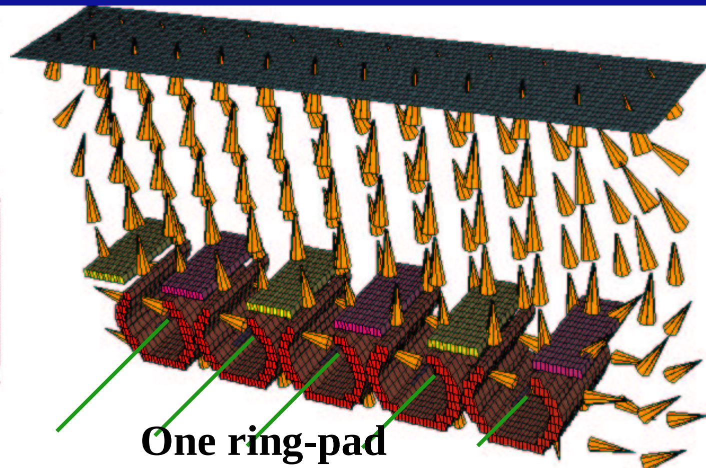
Alternative TPC Readout?

- The quest for more signal!
  - Without increasing gas gain;
    i.e. avoid instabilities & aging;
  - Without increasing primary ionization;
    i.e. the space charge problem;
- Integrated designs…
  - With higher component density and -safety
  - With better pulse shaping (ion tail problem)

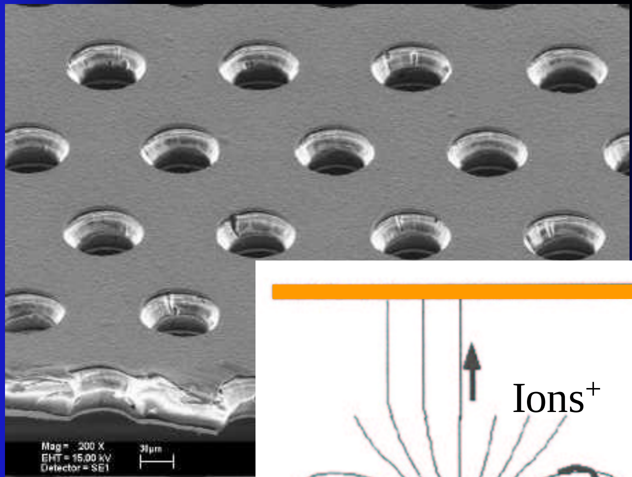
The Ring Cathode (RCC)

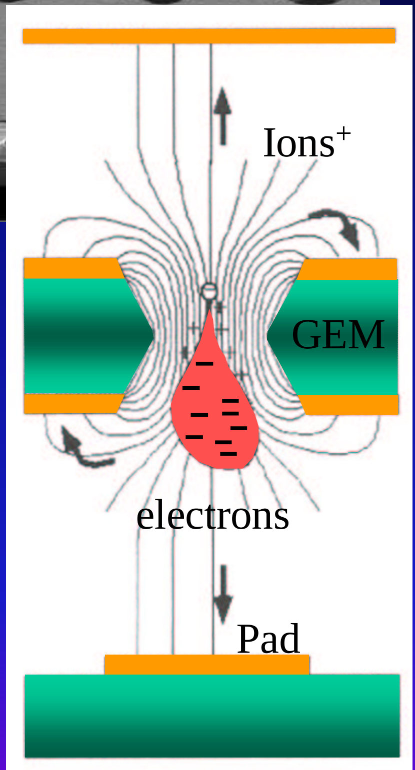
- Is a classical proportional chamber, with
  - <u>3-dimensional</u> cathode structure (rings) to “catch” more ions;
  - Induced signal ~ 4 (2) times that of classical TPC with (without) field wires. ☺
  - Gating scheme critical: positive ion feedback not suppressed to the 10^{-4} level ☹
  - Only one wire plane (anodes) ☺





The GEM Readout

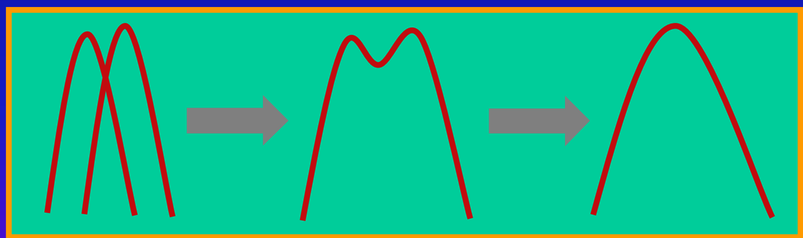




- Perhaps the most promising future readout technique:
  - No more wires! ☺
  - High gain, and good electron collection efficiency (~ 95%). ☺
  - Essentially no *E* x *B* - effect. ☺
  - Pad signal ~ 100% electron induced (no ion tail) ☺, but no PRF. ☹
  - Ion suppression not at the level of 10^{-4} .☹
  - Spark rate of ~ 10^{-3} Hz (background), and 10^{-3} sparks per incident a-particle. ☹
  - Gap uniformity for dE/dx crucial. ☹

Other Ways to Improve?

- What, if B-field were higher?
  - Curling tracks score additional hits and hence increase occupancy and space charge.
  - Increase distortions due to *E* x *B*-effect in drift volume.
  - Cold gas has practically no diffusion suppression ($\omega\tau$).
- Better pattern recognition algorithms?
  - Faster processors could run on more combinatorials (secondary vertices), but cluster-overlap limits resolving power.



Other Ways to Improve

- Gases?
  - No dramatic (factor 10) increase in v_d feasible.
  - If Ne-CO_2 remains prime choice, HV would become excessive for long paths.
  - 100 kV are already tricky to handle.
  - Given all odds (flammability, toxicity, corrosiveness, aging, HV and cost) our (ALICE's) choices are extremely limited if not exhausted.

The (ALICE) TPC, is it…

- a test bench for tracking *beyond LHC*?
  - Powerful pattern recognition:
    - Occupancy (space-time-bins) ≤ 50%!
  - Conceptually simple device.
  - Robust construction,
    - but need tight control on mechanical, electrical & environmental parameters.
  - Adaptable & exchangeable readout techniques.
  - Proven technology in PEP4, ALEPH, NA49, STAR.

Yes, but…

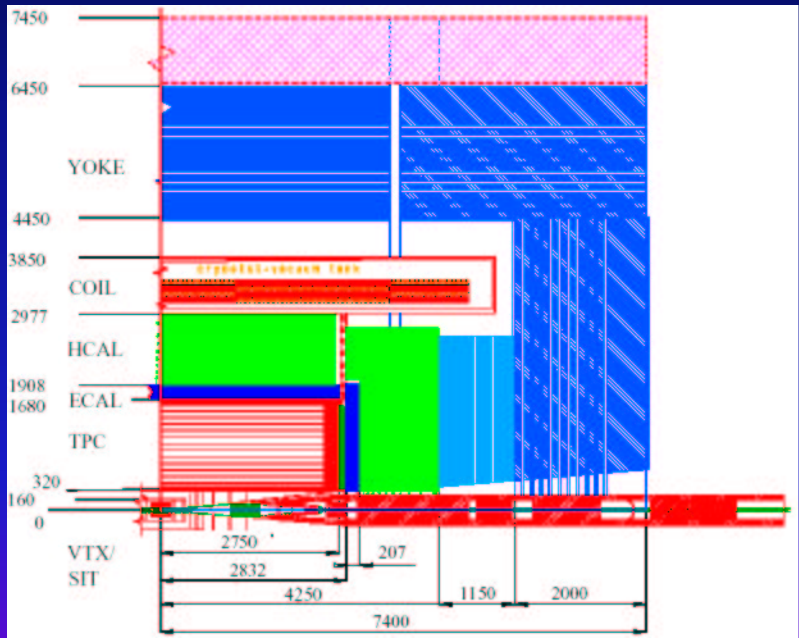
…The (ALICE) TPC…

- In hadron colliders the TPC is severely 'handicapped' from:
  - *Space charge accumulation:* Pb-Pb with $\mathcal{L} \leq 10^{27}$ cm^{-2} s^{-1}
  - *Long drift/memory time:* p-p: $\mathcal{L} \leq 3 \times 10^{30}$ cm^{-2} s^{-1}
    1 kHz maximum for chosen gas
- If $dN_{ch}/d\eta \sim s^{1/2}$ (RHIC!), abandon exclusive studies and search for inclusive/selective signatures --> abandon TPCs.
- Perhaps TPC ideally suited for lepton colliders

Outlook: Tracking at TESLA

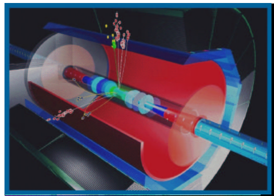
Relevant Machine Parameters:		TESLA-500	TESLA-80
E cm	[GeV]	500	80
Repetition rate	[Hz]	5	4
Beam pulse length	[μs]	90	0
No. of bunches/pulse		2	6
Bunch spacing	[ns]	3	6
Luminosity ($e^+ e^-$)	[$cm^{-2} s^{-1}$]	[illegible] 34	5[illegible] 34

- Substantially less background than at LHC.
- Well defined initial state, clean event signatures.



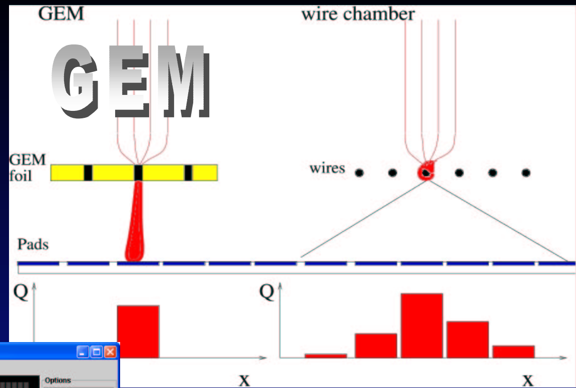
- Precise measurement of charged particle momenta
- High-resolution track finding for jet-physics & event pile-up
- dE/dx resolution of < 5% for good π-K separation
- Systematic effects below 10 μm!

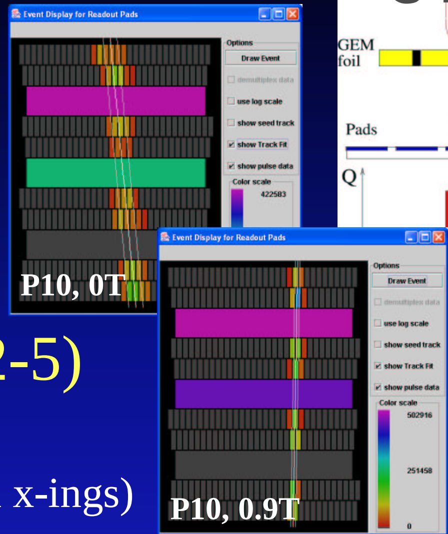
Courtesy: Stephan Roth, RWTH Aachen

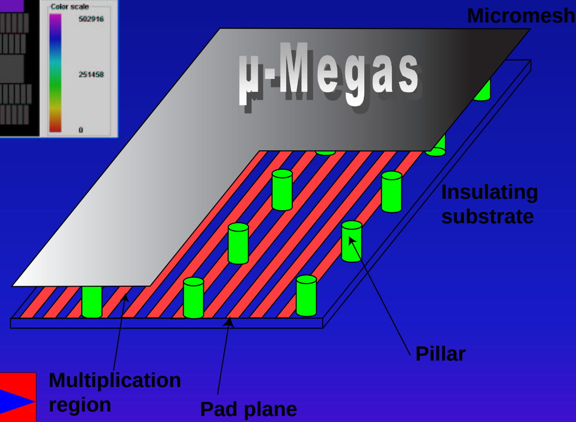


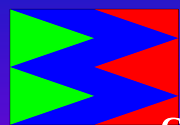
Outlook: A TPC for TESLA

- Large volume
  - r_i = 320 mm, r_{out} = 1700 mm, l = 2 x 2500 mm
  - V_{gas} = 38 m^3
- Light structure
  - x/x_0 ~ 3% to outer field cage
- High magnetic field: B = 4T
- 'Fast' gas: Ar-CO_2-CH_4 (93-2-5)
  - E_d = 230 V/cm (60 kV max)
  - v_d = 4.6 cm/µs (55 µs max = 160 bunch x-ings)
  - $D_{t(l)}$ = 70 (300) µm/$cm^{1/2}$ @ 4T
  - Average $\sigma_{r\phi}$: 100 or 150 µm (dep. on gas: P10 or above)
- Readout: Micro-pattern devices
  - GEM (pads, chevrons of 1-2 mm width)
  - Micromegas



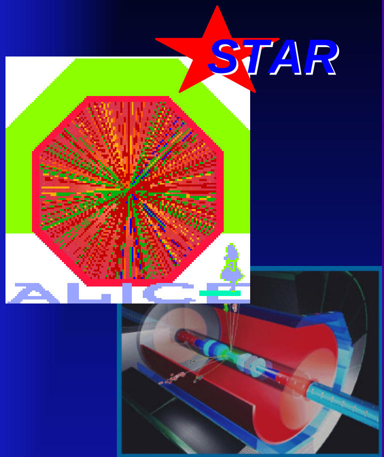






Courtesy: Stephan Roth, RWTH Aachen

TPCs: Today, 2007 and 2014?



Relevant Parameters:		STAR TPC	ALICE TPC	TESLA TPC
Inner radius	[mm]	500	8	2
Outer radius	[mm]	2000	5	700
Length	[mm]	2000	5000	5000
Volume	$[m^3]$	9	9	8
Material x/x_0	[%]	3	3	3
Pad size	$[mm^2]$	850 990	7 85)	8
No. pad rows		5	6	200
Total No. of pads		58	557	20000
Magnetic field B	[T]	005	005	4
Gas		$_4$(90)	$_2$(90)	$_4$O $_2$(92)
Drift field E_d	[V/cm]	5	400	2
Drift velocity v_d	[cm/µs]	55	2	6
Total drift time	[µs]	8	8	55
Maximum HV	[kV]	2	100	600
Diffusion transverse	$[µm/cm^{1/2}]$	205T	2	7
Diffusion logitudinal	$[µm/cm^{1/2}]$	3	2	80
Resolution in r-ϕ	[µm]	500200	80200	70
Resolution in z	[µm]	1000800	60200	60100
dE/dx resolution	[%]	8	7	3
Tracking efficiency	[%]	8	9	9

14 Years Down the Road To LHC: Lesson 2

1990 Generic R & D — Design & Prototyping — Construction & Assembly — Commissioning — Physics ?

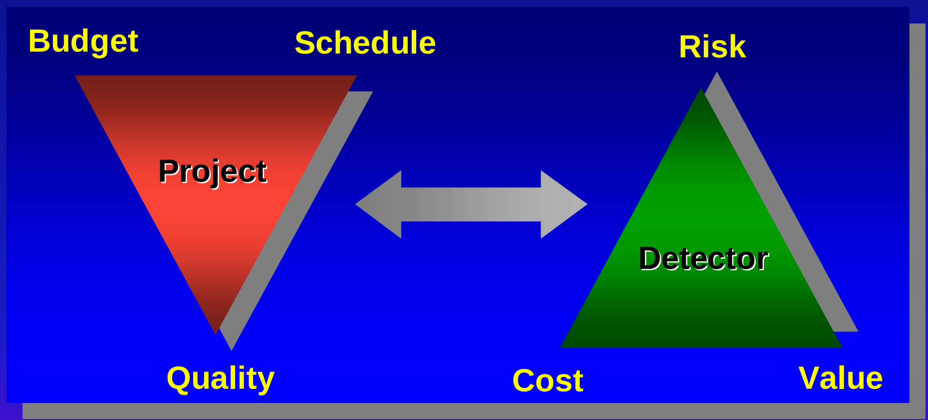
- The life cycle of an LHC project is ~20 y!
  - Will we be able to attract students henceforth?
    - “Young people are impatient”
- Unfocused planning due to LHC schedule slip
  - “In ten years from now we’ll be running!”
  - “Failure to prepare is prepare for failure!” No contingencies!
- Question: Competition over complementarity?
  - Shouldn’t we have more diversity in the physics program?
- The fear of change.
  - We stick to conservative methods and traditional thinking.

Changes to face, now and later

- Non-traditional budget restrictions
- Highly complex and diverse projects
  - Technically, geographically, financially, culturally…
- Increased product complexity & demands on quality
  - Detector performance ––> data quality
  - --> Our credibility & reputation --> share holding
- People will disappear, knowledge must stay!
  - Need good documentation (EDMS), traceability, continuity
- Multinational organizational structures
  - Focusing on equity sharing & equally ranking partnerships;

From "Result-" to Project Orientation

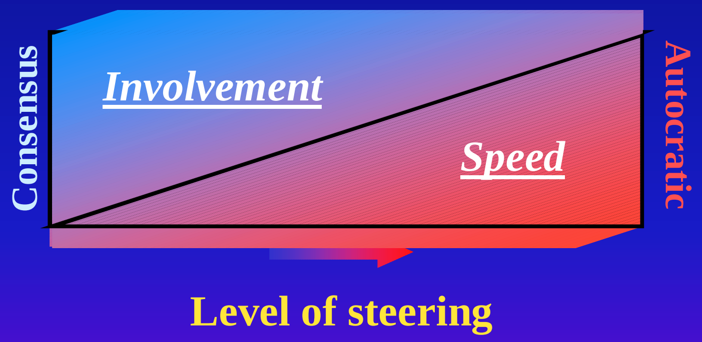
- Create awareness of project management, i.e. ensure:
  - Completion ⇒ deliver on time and within budget!
  - Adequateness ⇒ build for purpose!
  - Compliance ⇒ conformity, performance.



- Perform:
  - Risk analysis and
  - rigorous contingency assessment.

From Dogmatic to Pragmatic

- Accept PM as a tool to achieve a common goal!
  - Governance (leadership) is not dictatorship.
  - Applying rules is not ruling.
  - Controlling is corrective monitoring.
- Apply a balanced level of central steering:



- The *“Checks-and-Balance”* approach, but
- High level of steering during construction and assembly

Final Thoughts

- Technical:
  - Today's (!) LHC tracking detectors have opened a new era of state-of-the-art technologies, and <u>are</u> bench marks for developments beyond the LHC.
  - TPCs will probably disappear from hadron colliders and return to their origin, e^+-e^- (μ^+-μ^-) machines where, in conjunction with micro-pattern devices, they constitute the ideal and most cost-effective central tracking systems.
- General:
  - The LHC is the gateway to the future, provided…

    …that overall coordination and rational in project management methods are implemented and carried out by dedicated project teams in a <u>'check and balance' spirit with central steering</u>.