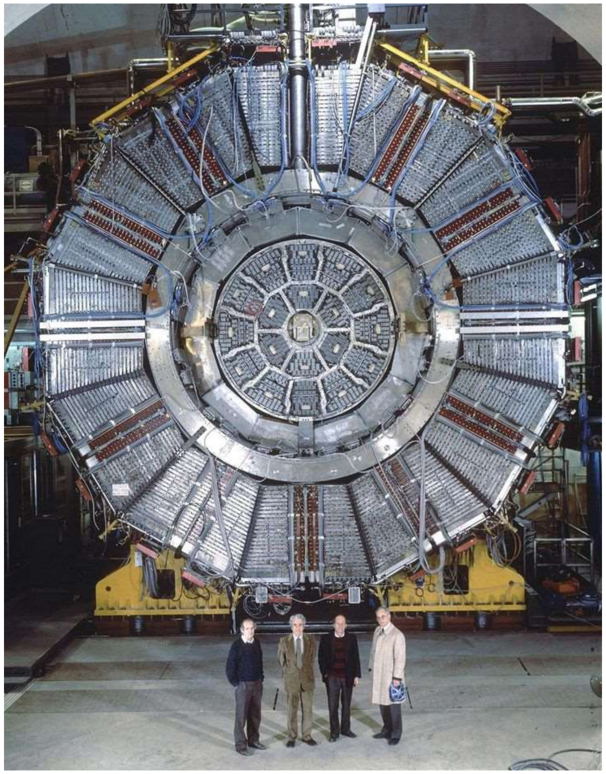
The Amazing ALEPH TPC

Tracking the Elusive

50 Years of High Precision Measurements with Luigi Rolandi



Scuola Normale Superiore – November 7th 2025

After FRAMM

- For many of us FRAMM was an extraordinary school for experimental physics
  - We had the possibility to learn and practice all the aspects of the activities of an experiment
    - Designing, building and commissioning various kind of detectors
    - Writing DAQ, reconstruction and analysis software
    - Running the experiment and collecting data
    - Performing various data analyses
- However
  - Around us there were experiments like CDHS, CHARM … SLAC, Fermilab
  - Physics like neutral and charged currents, search for W and Z
- Lorenzo Foa was conscious that
  - There was the possibility to build around the Pisa group a collaboration to give important contribution to some of the new proposed experiments
  - He was also conscious that the group of young physicists grown in FRAMM could play important roles in the new experiments
- Lorenzo choice went towards ALEPH
  - Lorenzo steered the constructions capabilities towards the Hadron Calorimeter
  - Lorenzo also encouraged young people to join the efforts for the ALEPH central detector

The origins

- High precision measurements require an high performance detector
  - LEP was an excellent $e^+ e^-$ collider
  - ALEPH was an high performance detector
  - The ALEPH TPC was one of the most performing detectors at the time

- The road we followed to design the ALEPH TPC is the subject of this talk
  - Gigi played a fundamental role in this project
- The ALEPH TPC was a very complex detector
  - In many field there were important contributions from many laboratories
    - Building of the sectors, Inner and Outer Field Cages, Gating, gas system, laser system, front end electronics, digitizers, readout processors …
  - Being here in Pisa I cannot avoid to mention the design and construction od the TPP (the TPC readout processor): a FASTBUS module build around the innovative Motorola 68020 processor
    - Key people were Francesco Fidecaro, Roberto Amendolia, Diego Pasuello, Pier Simone Marrocchesi
  - However I will concentrate in that part in which Gigi and myself gave some contribution
    - I would say … some important contribution

The origins

- We were very young
  - Coming for the FRAMM collaboration
  - We saw ALEPH under the leadership of Jack Steinberger as a big opportunity to become part of one of the most important physics community at that time
- We joined the TPC group lead by Juergen May
- Again, I want to stress the role of Lorenzo who always encouraged us

Once Upon A Time …

- There was a very very young collaboration

Bari-CERN-Demokritos Athens-Dortmund-Ecole Polytechnique Palaiseau-
Edinburgh-Glasgow-Heidelberg-Lancaster-MPI München-Orsay-Pisa-Rutherford
Saclay-Sheffield-Torino-Trieste-Westfield College London-Wisconsin Collaboration

LETTER OF INTENT

TO STUDY e^+e^- ANNIHILATION PHENOMENA AT LEP

Bari-CERN-Demokritos Athens-Dortmund-Ecole Polytechnique Palaiseau-
Edinburgh-Glasgow-Heidelberg-Lancaster-MPI München-Orsay-Pisa-Rutherford
Saclay-Sheffield-Torino-Trieste-Westfield College London-Wisconsin Collaboration

Geneva, 25 January 1982

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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25.03.1982

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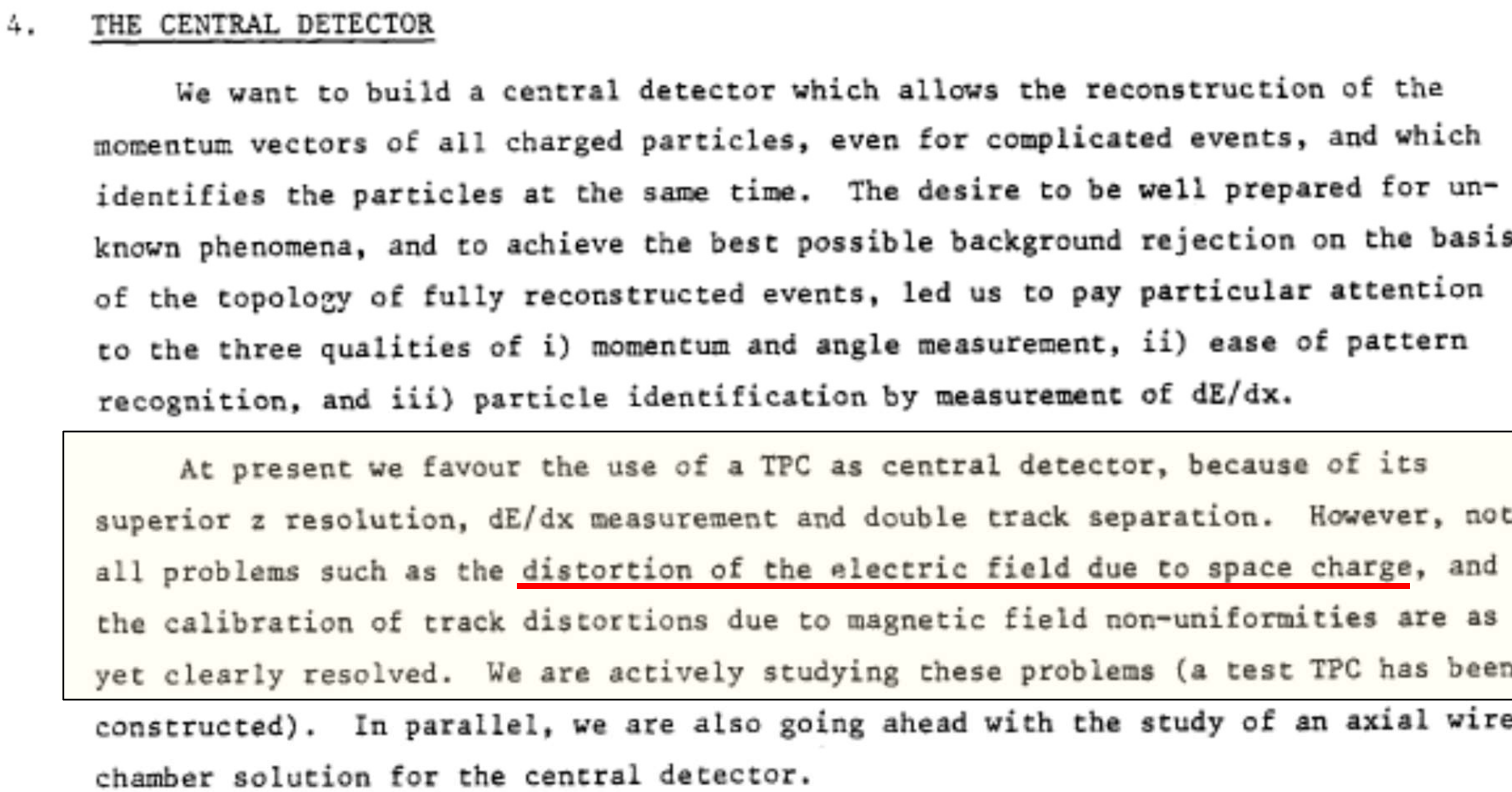
Letter of Intent

"A L E P H   D E T E C T O R"

(Apparatus for LEP PHysics)

The TPC in the ALEPH letter of intent



4. THE CENTRAL DETECTOR

We want to build a central detector which allows the reconstruction of the momentum vectors of all charged particles, even for complicated events, and which identifies the particles at the same time. The desire to be well prepared for unknown phenomena, and to achieve the best possible background rejection on the basis of the topology of fully reconstructed events, led us to pay particular attention to the three qualities of i) momentum and angle measurement, ii) ease of pattern recognition, and iii) particle identification by measurement of dE/dx.

At present we favour the use of a TPC as central detector, because of its superior z resolution, dE/dx measurement and double track separation. However, not all problems such as the distortion of the electric field due to space charge, and the calibration of track distortions due to magnetic field non-uniformities are as yet clearly resolved. We are actively studying these problems (a test TPC has been constructed). In parallel, we are also going ahead with the study of an axial wire chamber solution for the central detector.

The TPC had several unknowns

- In the 1982 ALEPH letter of intent
  - There where two options for the central tracking detector
    - A Time Projection Chamber
    - An axial wire chamber (Jet Chamber)
  - The goal was a $200\ \mu\mathrm{m}$ resolution on the sagitta measurement
- At that time the TPC was a very innovative detector featuring
  - Optimal measurement of the charged particles trajectory and momentum
  - Very good two-track resolution (3d coordinate measurement)
  - Charged particle identification using dE/dx
- The TPC was invented by David Nygren (LBL) for the PEP-4 detector at SLAC
- It was known that the "Berkeley TPC had problems
  - Particle trajectories were affected by distortions hard to correct
  - Probably due to space charge effects
    - In fact the detector was not equipped with a "gating system"
    - Space charge due to ions produced in the amplification region
      - Ions moving back to the drift region could generate track distortions
- There was also a second (smaller) TPC at Triumf
  - Its spatial resolution was much worst than what we quoted in the LOI

The TRIUMF TPC

- In that months, at TRIUMF the commissioning of a TPC (built for a search of Leptonic Number violation in $\mu^- Z \to e^- Z$) was in progress
  - Preliminary results presented at a SLAC Conference showed a "not very good" spatial resolution
- Spatial resolution worst than $400~\mu\text{m}$ @ $0°$
- In the LOI ALEPH aimed at a much better resolution
- The LEPC asked ALEPH to explain how we thought to achieve a $200~\mu\text{m}$ resolution
  - Lorenzo pushed the young people of the group to join the ALEPH TPC group lead by Jurgen May
- Lorenzo became full professor in Trieste in 1978
  - Many of the young researchers working in FRAMM fascinated by the ALEPH adventure, joined Lorenzo in Trieste:
    - Gigi Rolandi, Francesco Ragusa, Fernando Liello, Giovanni Batignani

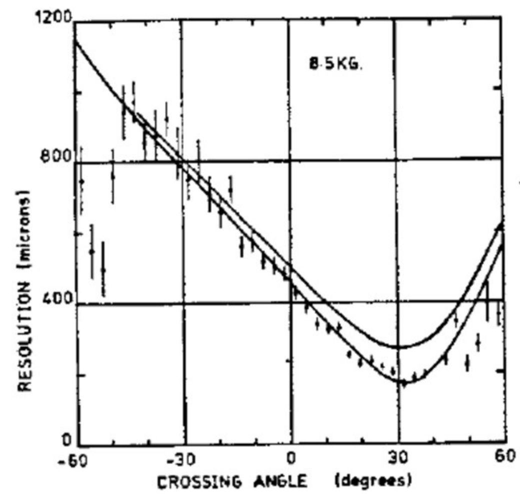
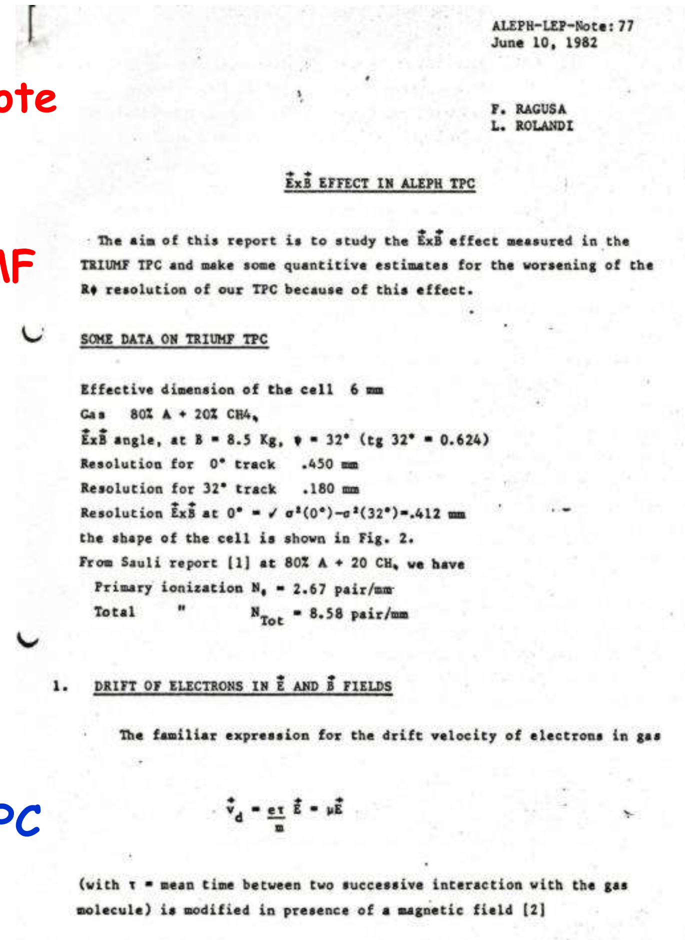


Fig. 9. The resolution as a function of crossing angle θ. The data are for 3.5 cm drift distance and B=8.5 kG. The curves are produced from Eq. (14). The lower (upper) curve uses z=3.5 cm (34 cm).

The TPC space resolution

- We started to work on the problem
  - On June 10th 1982 we published our first TPC note
- Main results
  - Complete formula of v_d in magnetic field
  - Understanding of the differences ALEPH-TRIUMF
    - Amplification cell dimensions
    - Contribution ow many sense wires
  - Possibility for further improvements
    - Correction of the $r-\phi$ measurement using the signal from the sense wires
- The results were presented
  - At the ALEPH plenary meeting
  - To the LEPC
- Jack was always convinced that our work was fundamental for the approval of ALEPH by the LEPC

- Jack was also convinced the TPC group was much more advanced than the Jet Chamber group
  - The TPC/Jet Chamber was resolved in favor of the TPC



ALEPH-LEP-Note: 77
June 10, 1982

F. RAGUSA
L. ROLANDI

$\vec{E}\times\vec{B}$ EFFECT IN ALEPH TPC

The aim of this report is to study the $\vec{E}\times\vec{B}$ effect measured in the TRIUMF TPC and make some quantitive estimates for the worsening of the Rϕ resolution of our TPC because of this effect.

SOME DATA ON TRIUMF TPC

Effective dimension of the cell 6 mm
Gas 80% A + 20% CH_4,
$\vec{E}\times\vec{B}$ angle, at B = 8.5 Kg, ϕ = 32° (tg 32° = 0.624)
Resolution for 0° track .450 mm
Resolution for 32° track .180 mm
Resolution $\vec{E}\times\vec{B}$ at 0° = $\sqrt{\sigma^2(0°)-\sigma^2(32°)}$ = .412 mm
the shape of the cell is shown in Fig. 2.
From Sauli report [1] at 80% A + 20 CH_4 we have
Primary ionization N_0 = 2.67 pair/mm
Total " N_{Tot} = 8.58 pair/mm

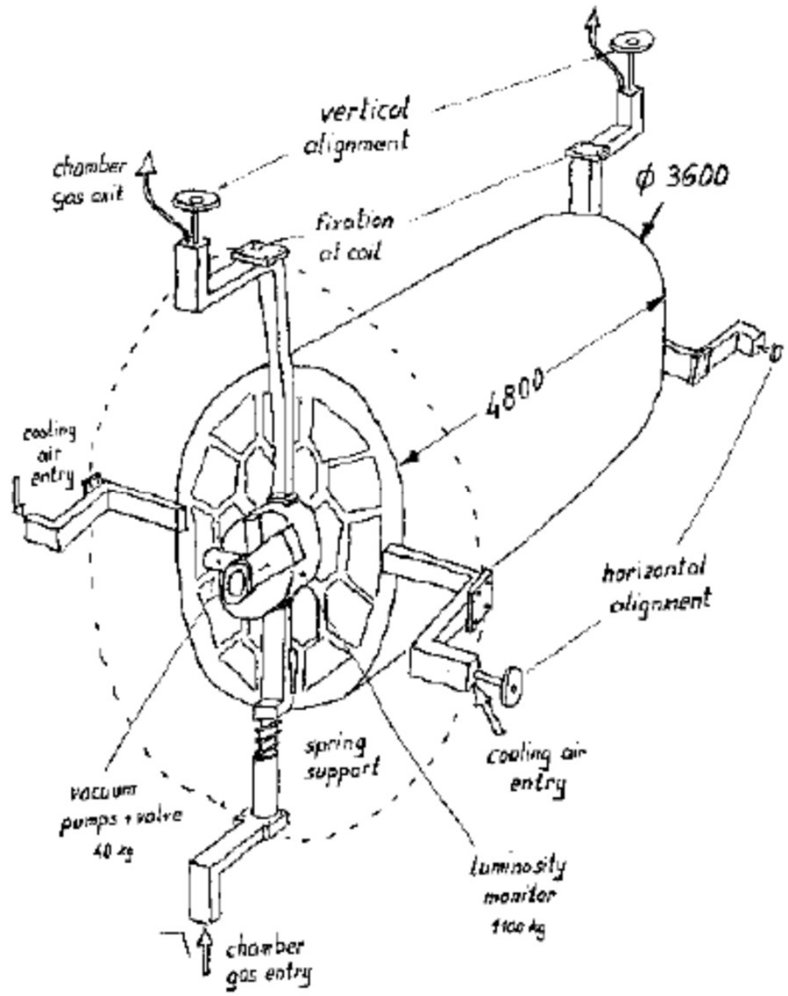
1. DRIFT OF ELECTRONS IN $\vec{E}$ AND $\vec{B}$ FIELDS

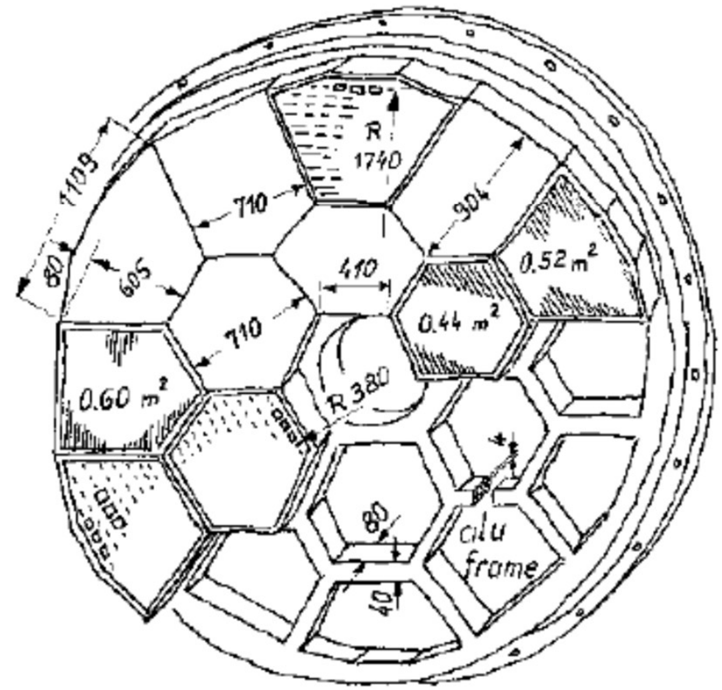
The familiar expression for the drift velocity of electrons in gas

$$\vec{v}_d = \frac{e\tau}{m}\vec{E} = \mu\vec{E}$$

(with τ = mean time between two successive interaction with the gas molecule) is modified in presence of a magnetic field [2]

The ALEPH Time Projection Chamber

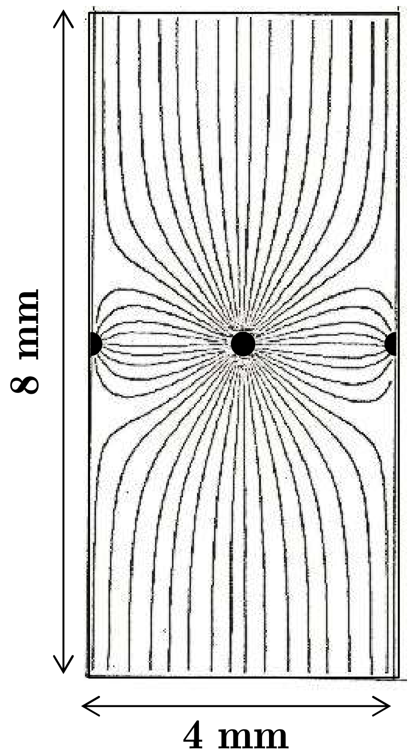


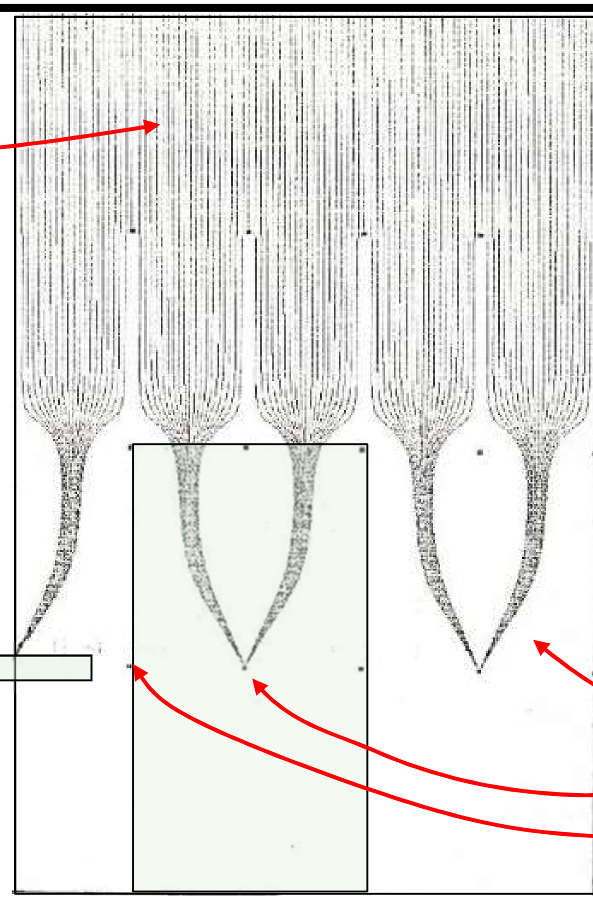


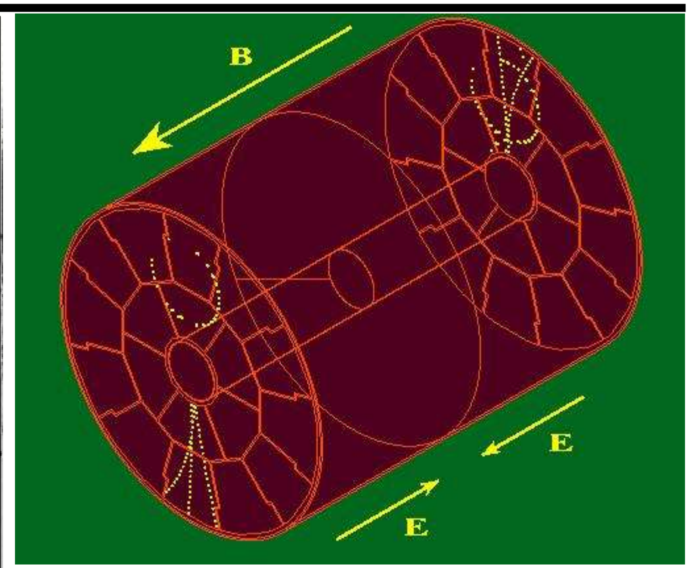
Electric Fields of the ALEPH TPC[1]

Drift Region

Amplification Cell







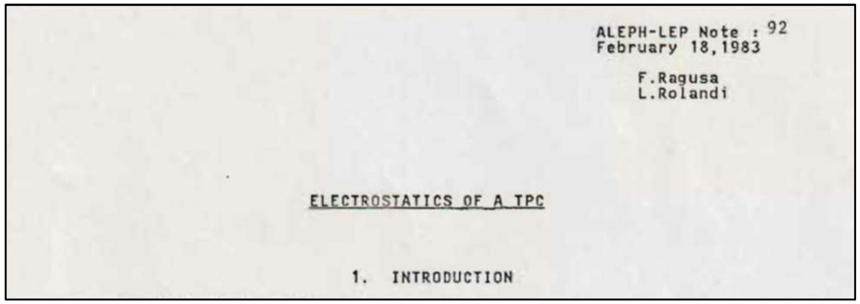
Amplification Region

- Sense wire (amplification)
- Shaping field wires

- Near the sense wire the E×B product is along the wire
- E×B has opposite directions to the left or to the right of the wire

- [1]ALEPH-NOTE 92 February 18th 1983

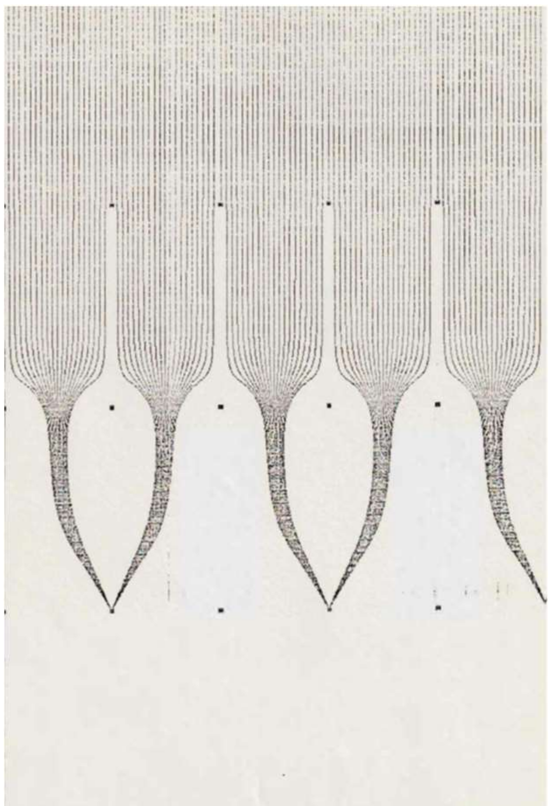
Electrostatic of a TPC: gating grid

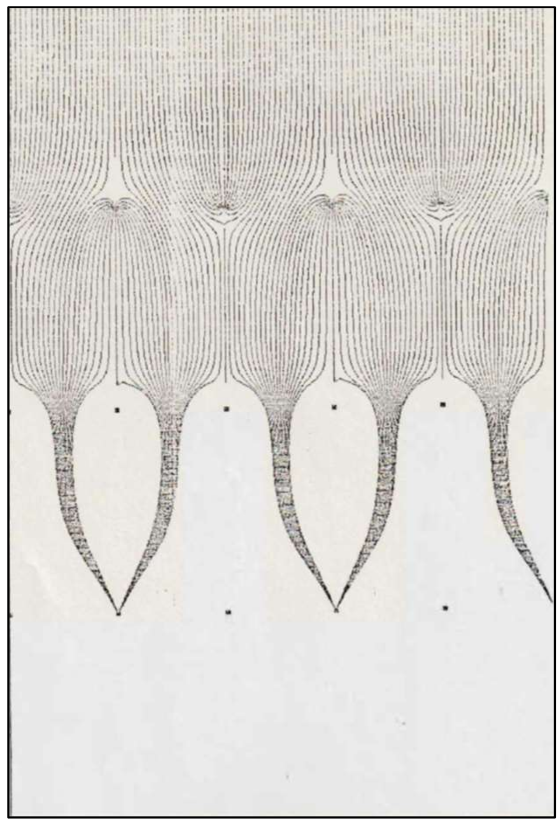

ALEPH-LEP Note : 92
February 18, 1983

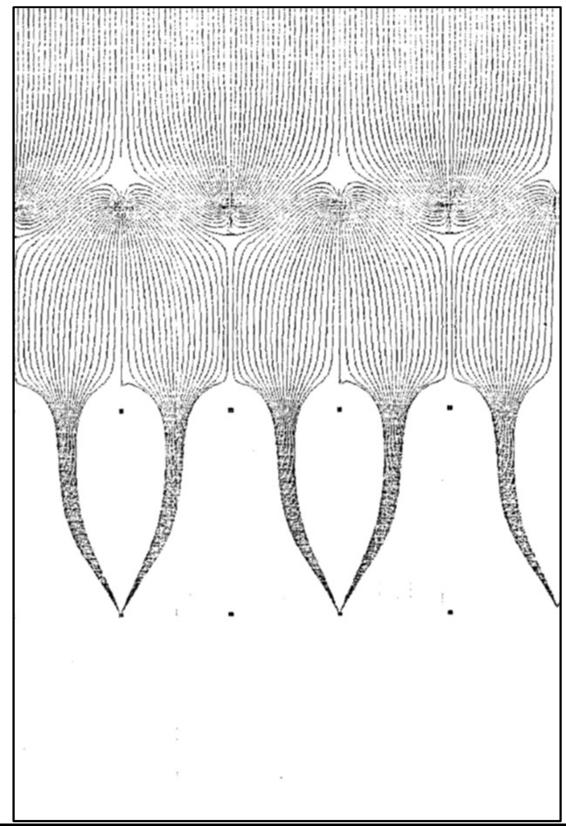
F.Ragusa
L.Rolandi

ELECTROSTATICS OF A TPC

1. INTRODUCTION







Electron drift velocity in magnetic field

- The Drift Chamber Bible (F. Sauli[1]) devoted few lines to the electrons drift velocity in presence of a magnetic field

  In the case of a movement in a constant electric and magnetic field, the swarm will drift along a straight line at an angle α_H with the field lines, and with a velocity $w_H \neq w$. The same simple theory that gives the expression (14) allows one to write the effect of a magnetic field H applied in a direction perpendicular to the electric field[21] as follows:

  $$w_H = \frac{w}{\sqrt{1+\omega^2\tau^2}}, \qquad \omega = \frac{eH}{m} \qquad \tan\alpha_H = \omega\tau$$

  - At that time wire detectors had configurations of E and B fields very different from the one of TPCs
  - Sauli's treatment neglected effects that were of fundamental importance
- We arrived to a paper[2] of the 50's thanks to which we derived the formula[3]

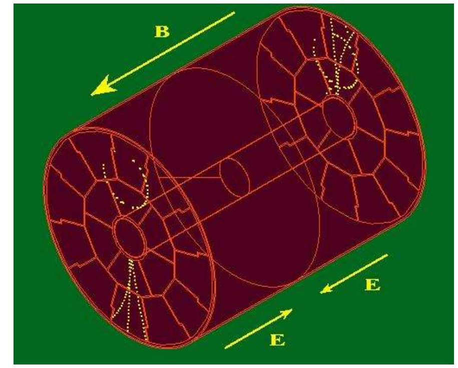
$$\mathbf{v}_d = \frac{\mu}{1+\omega^2\tau^2}\left[\mathbf{E} + \frac{\omega\tau}{B}\mathbf{E}\times\mathbf{B} + \omega^2\tau^2\frac{\mathbf{E}\cdot\mathbf{B}}{B^2}\mathbf{B}\right]$$

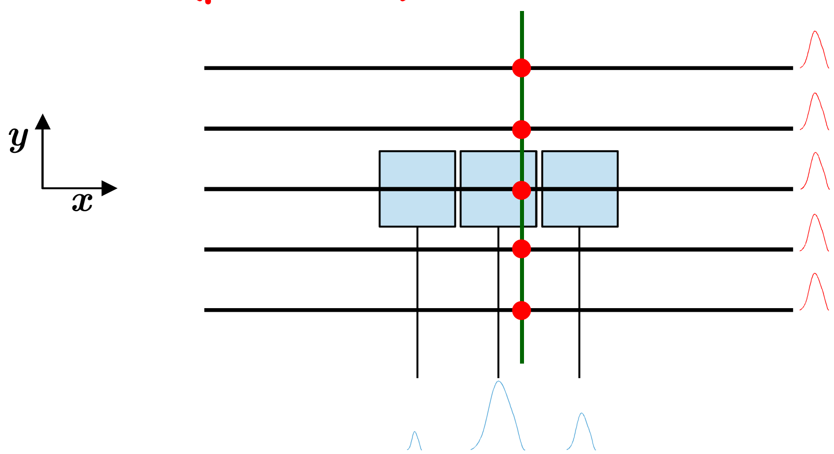
- Thanks to this formula we were able to understand the SLAC and the TRIUMF TPCs and how to design our detector avoiding their problems

- [1]F. Sauli, Principle of Operation Multiwire Proportional And Drift Chambers – CERN 77-09
- [2]W. Allis, Motion of Ion And Electrons – Handbuch Der Physik XXI Springer (1956)
- [3]F. Ragusa, L. Rolandi E×B effect in ALEPH TPC – ALEPH-LEP Note 77 (10.06.1982)

Measurement of the $r-\phi$ coordinate

- A charged particle trajectory in the TPC (a track) …
- The measurement of the projection of the track on the $r-\phi$ plane (endplate) is obtained:
  - From the y position of the wire (of the pad row) (r)
  - From the x position along the wire of the electrons avalanche (point-like) (ϕ)





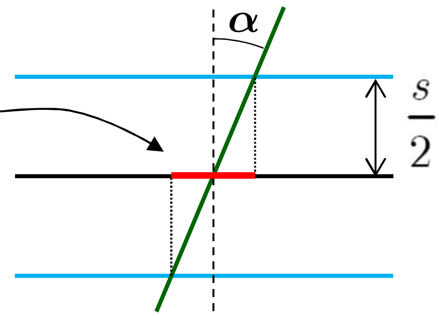
For simplicity the field wires are not drawn

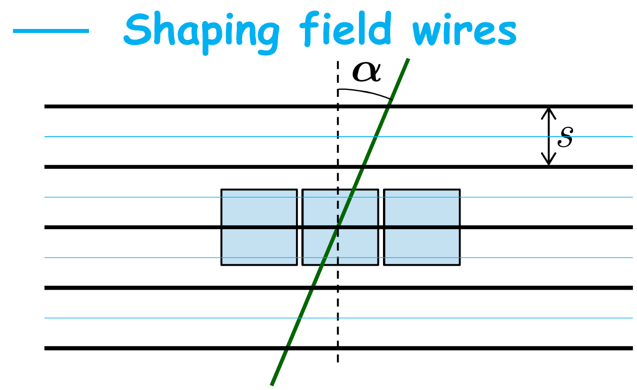
  - The avalanche position is measured through the signals induced on the pads
- In ALEPH, the pads dimension $(6\ \mathrm{mm})$ and the wires spacing $(4\ \mathrm{mm})$ implied that the pads collected the signals induced by the avalanches of 5 wires
  - Of course the furthest wires induce smaller signals on the pads
- In this model the ϕ space resolution σ_0 is determined by pad electronic noise

Angular Effect

- If the track is inclined respect to the wire, the resolution worsens
  - The avalanche is not point-like anymore and spreads along the wire for a width Δ

$$\Delta = \left| s \cdot \mathrm{tg}\,\alpha \right|$$



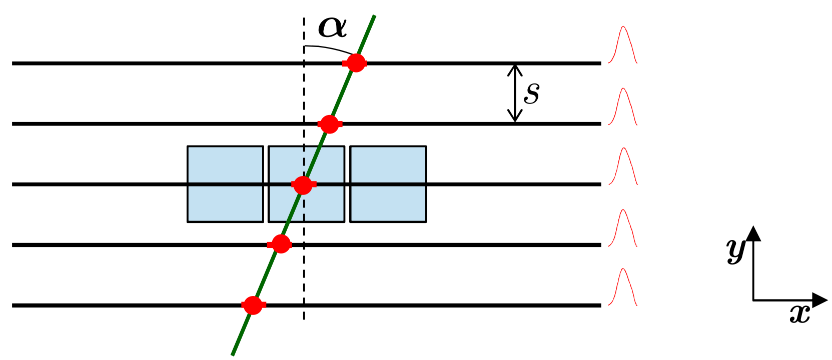


- The ionization is finite
  - N_p primary clusters; the coordinate is average of the positions of the clusters (centroid)
  - The centroid precision is

$$\sigma_a = \kappa \frac{\Delta}{\sqrt{12 N_p}} = \kappa \frac{s}{\sqrt{12 \kappa N_p}} \cdot \left| \mathrm{tg}\,\alpha \right|$$

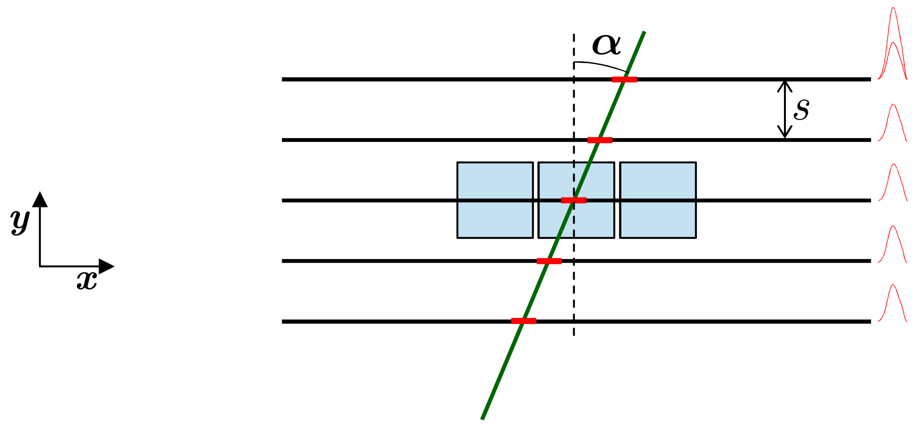
The factor $\kappa \sim 1.5$ accounts for the fluctuations on the clusters size

- Of course, this effect is present on all the wires



Angular Effect

- The charge collected by every wire (used for dE/dx particle ID) fluctuates
  - Landau Fluctuations
- Landau fluctuations worsen the space resolution



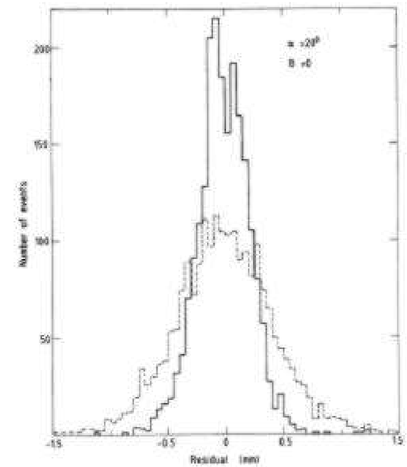
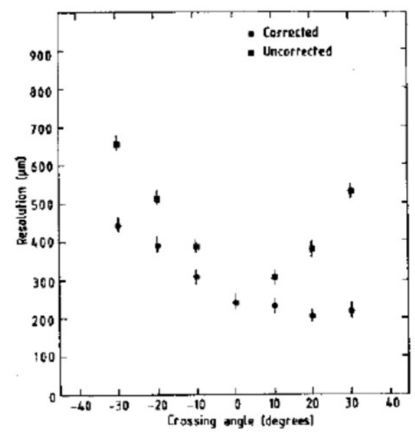


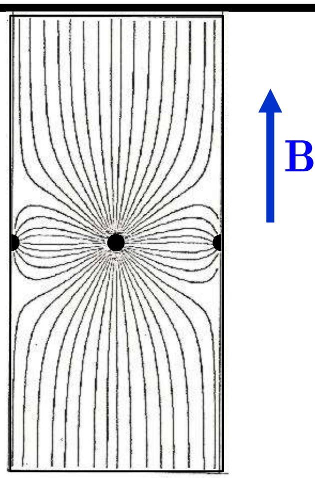
Fig. 4. Residual distribution for $\alpha = 20°$ and $B = 0$. Dashed line: uncorrected data. Solid line: data corrected for centroid shift.

- We understood that position measurement could be corrected using the measurements of the charge collected by the wires involved
  - Test performed in FRAMM using a TPC prototype
  - ALEPH-NOTE 83 October 12th 1982
  - Wien Wire Conference February 15th 1983
  - Vancouver Conference June 23rd 1983



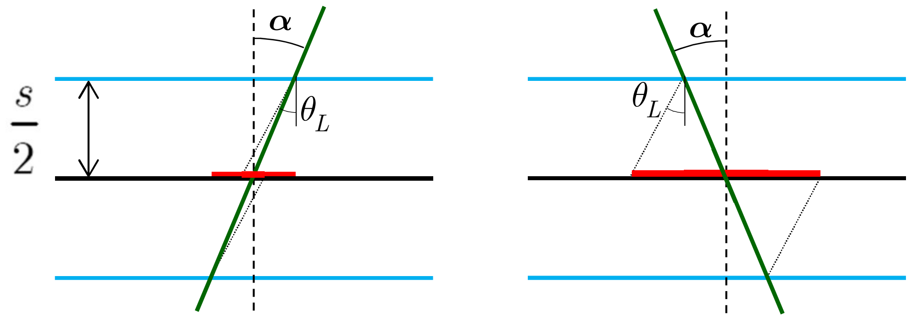
Angular Effect and E×B

- The magnetic field modifies the charge collection process
  - The B field is perpendicular to the sector (wires plane)
  - In the amplification region $\omega\tau \sim 0.6$ ($\theta_L \sim 30°$, $\mathrm{tg}\theta_L = \omega\tau$)
  - The E×B product is parallel to the wire
  - The width Δ' along which the ionization spread is modified



$$\mathbf{v}_d = \frac{\mu}{1+\omega^2\tau^2}\left[\mathbf{E} + \frac{\omega\tau}{B}\mathbf{E}\times\mathbf{B} + \frac{\omega^2\tau^2}{1+\omega^2\tau^2}\frac{\mathbf{E}\cdot\mathbf{B}}{B^2}\mathbf{B}\right]$$

Shaping field wires



$$\Delta = s \cdot \left|\mathrm{tg}\,\alpha\right| \rightarrow \Delta' = \left|s\,\mathrm{tg}\,\alpha - s\,\mathrm{tg}\,\theta_L\right|$$

- The resolution becomes

$$\sigma_a = \kappa\frac{\Delta'}{\sqrt{12N_p}} = \kappa\frac{s}{\sqrt{12N_p}} \cdot \left|\mathrm{tg}\,\alpha - \mathrm{tg}\,\theta_L\right|$$

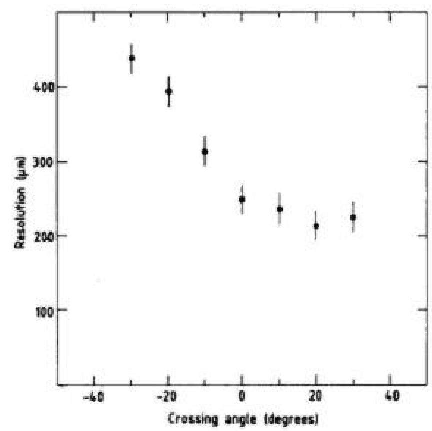
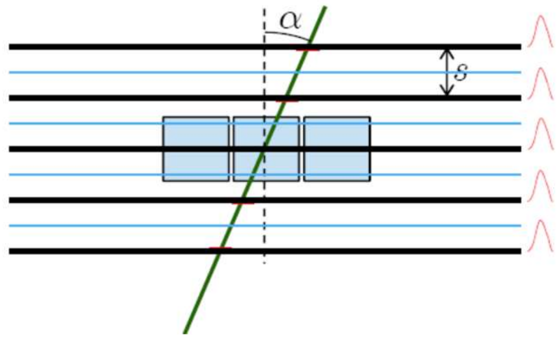


Fig. 6. Plot of the resolution vs α for data at $B = 15$ kG.

Long radial pads



- The described investigations (collected in 1) can be summarized with the formula

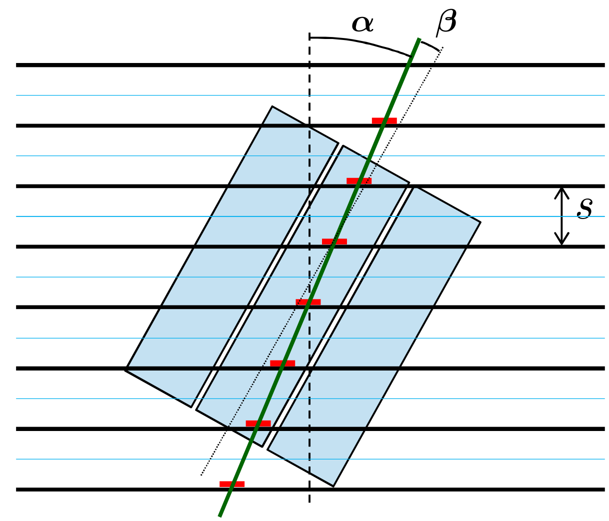
$$\sigma^2(\alpha) = \sigma_0^2 + \sigma_a^2(\mathrm{tg}\,\alpha - \mathrm{tg}\,\theta_L)^2 + \sigma_F^2\,\mathrm{tg}^2\,\alpha$$

- Angle α is used to parametrize two effects (N_F = number of wires influencing the hit pads)
  - Spread of the avalanche on the wire σ_a ~340 μm
    - α measured from the normal to the wire
    - σ_a decreases increasing N_F
    - σ_a depends on wire spacing s
  - Fluctuation of charge on the wires σ_F ~1000 μm
    - α measured from the normal to the pad row
    - σ_F increases when increasing N_F
      - N_F also depends on the pad length
  - Corrections using the wires reduce σ_F σ_F ~240 μm
    - However, corrections using the wires cannot applied always

- [1]ALEPH Technical Report 1983 - LEPC 83-2 May 15th 1983

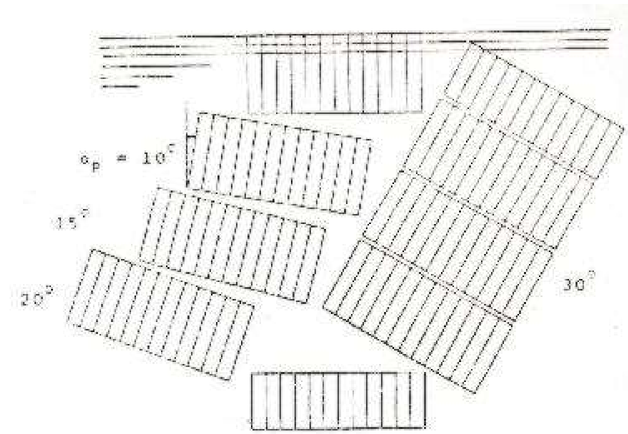
Long radial pads

- Jack proposed an innovative improvement: use long radial pads
  - Long pads to increase the number of wires N_F contributing to the pad signal
  - Radial pads to reduce (~eliminate) the angular effect due to the angle track – pad row axis
    - Various aspects of the problem are studied and results published in two internal notes
- The resolution parametrization becomes

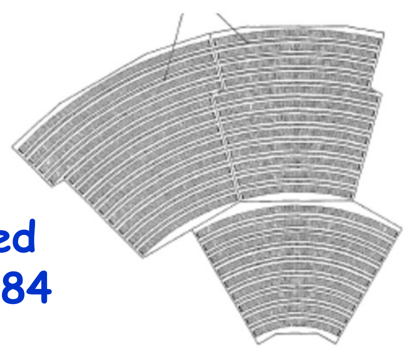


$$\sigma^2(\alpha) = \sigma_0^2 + \sigma_a^2(\mathrm{tg}\,\alpha - \mathrm{tg}\,\theta_L)^2 + \sigma_F^2\,\mathrm{tg}^2\,\beta$$

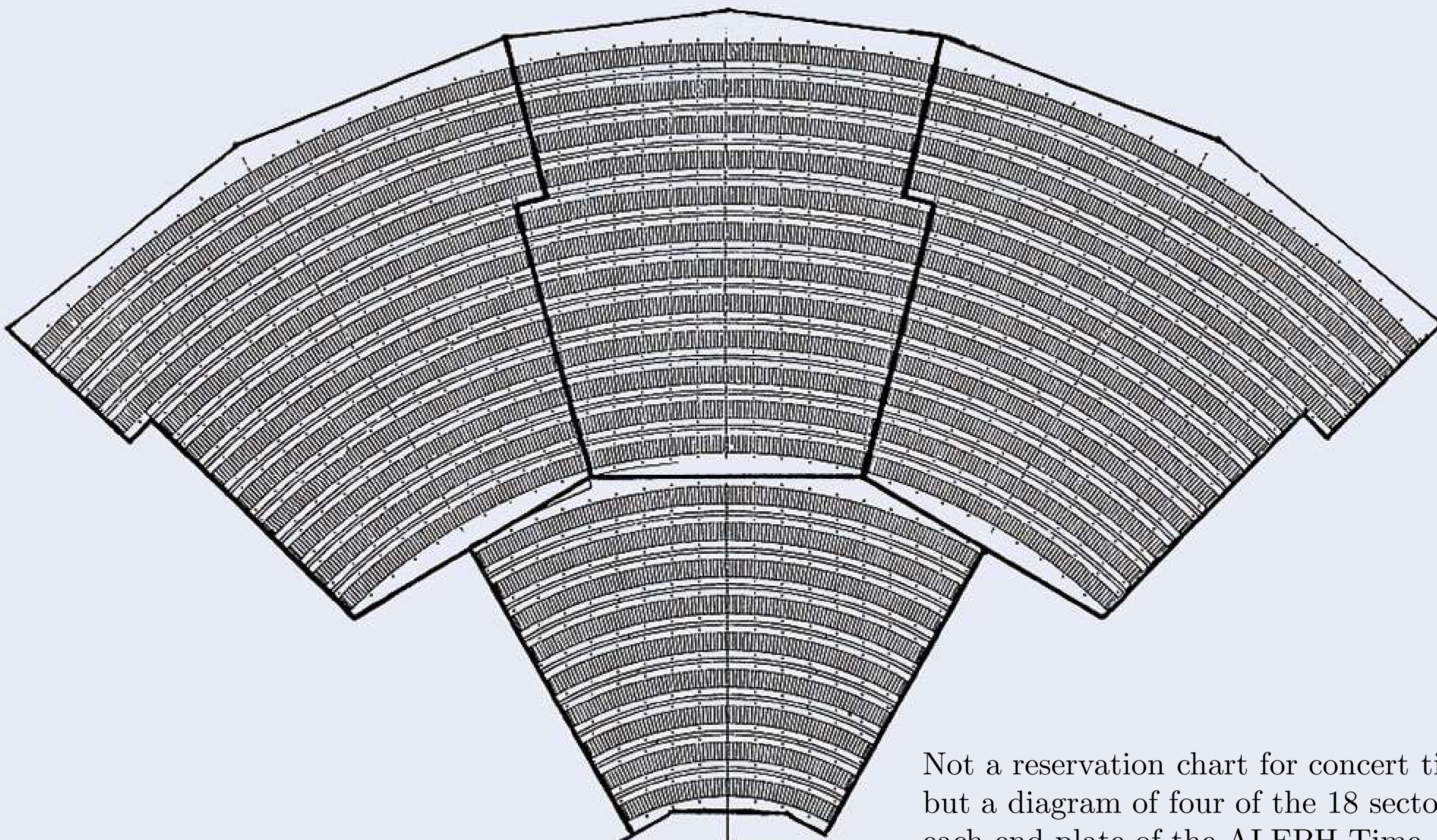
  - For high momentum tracks β is very small
- The solution was studied experimentally
  - A small prototype was built by P.S.Marrocchesi: the TPCina



- The pad row design was finalized in the Design Status Report 1984



CERN Courier 1 September 1984



Not a reservation chart for concert tickets but a diagram of four of the 18 sectors for each end-plate of the ALEPH Time Projection Chamber, showing the arrangement of some of the 22 000 readout pads.

Non-uniformity of the E and B fields

- The drift velocity in presence of electric and magnetic field is

$$\mathbf{v}_d = \frac{\mu}{1+\omega^2\tau^2}\left[\mathbf{E} + \frac{\omega\tau}{B}\mathbf{E}\times\mathbf{B} + \omega^2\tau^2\frac{\mathbf{E}\cdot\mathbf{B}}{B^2}\mathbf{B}\right]$$

  - When $\omega\tau << 1 \rightarrow \mathbf{v}_d = \mu\mathbf{E}$

  - When E and B are parallel $\mathbf{v}_d = \mu\mathbf{E}$
    - In fact

$$\mathbf{E}\times\mathbf{B} = 0 \qquad \frac{\mathbf{E}\cdot\mathbf{B}}{B^2}\mathbf{B} = \mathbf{E} \qquad \mathbf{v}_d = \mu\mathbf{E}$$

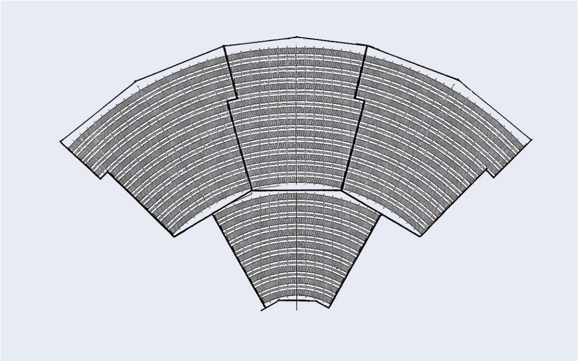
- In ALEPH, in the drift region, $\omega\tau \approx 9$
  - Typical gas mixtures used at that time: 20% CH4 – 80% Ar
  - CERN security asked to reduce to 10% CH4
    - This increased $\omega\tau$
  - When $\omega^2\tau^2 >> 1$ the last term becomes dominant

$$\mathbf{v}_d \rightarrow \mu E\frac{\mathbf{B}}{B}$$

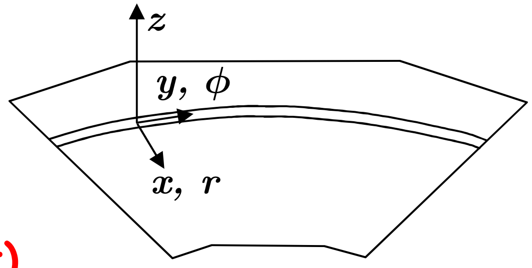
  - The drifting electrons follow the magnetic filed lines!

Non-uniformity of the E and B fields

$$\mathbf{v}_d = \frac{\mu}{1+\omega^2\tau^2}\left[\mathbf{E} + \frac{\omega\tau}{B}\mathbf{E}\times\mathbf{B} + \omega^2\tau^2\frac{\mathbf{E}\cdot\mathbf{B}}{B^2}\mathbf{B}\right]$$



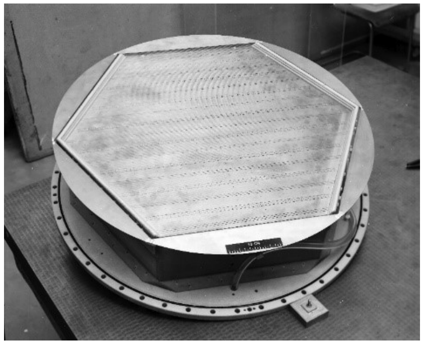
- Field non-homogeneities transverse to the z axis
  - The charge reaches the pad plane with a transversal displacement with respect to the position where was produced
- Dangerous distortions for the momentum measurement are those in the azimuthal direction ϕ (y)
  - Azimuthal distortions E_ϕ in the first term
    - Reduced by $(1+\omega^2\tau^2)$
  - Radial distortions E_r in the second term (cross product)
  - Azimuthal distortions B_ϕ In the third term
- PEP4 TPC – ALEPH TPC comparison

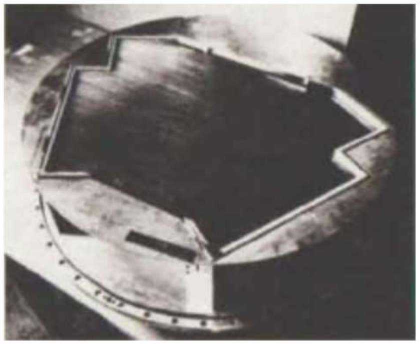


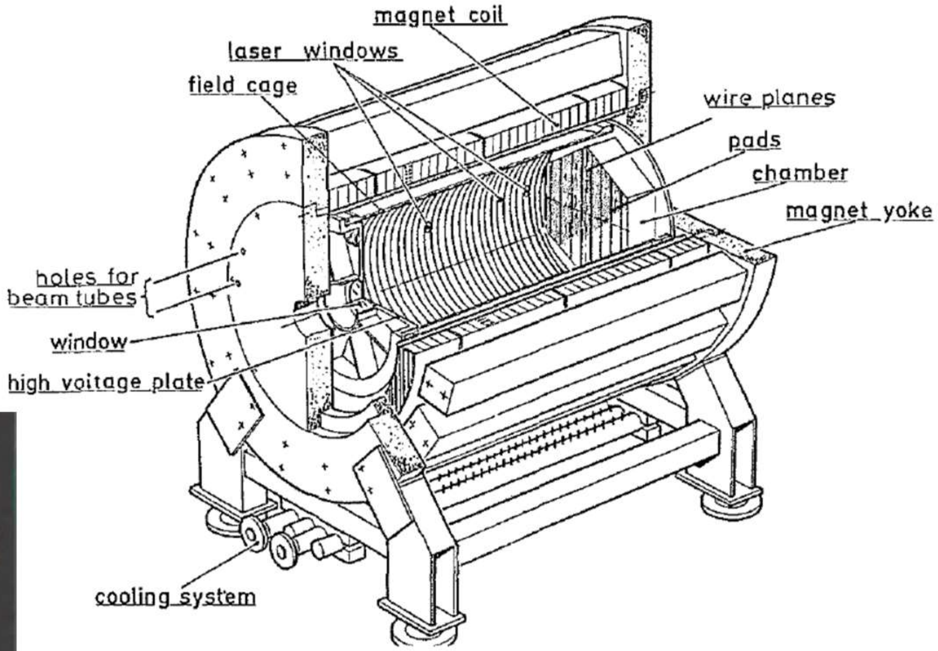
	$\omega\tau$	Electron trajectories	Notes
PEP4 TPC	0.3	Follow E lines	no gating, $\omega^2\tau^2 \ll 1$ Possibly large E_r, E_ϕ
ALEPH TPC	9.0	Follow B lines	gating, $\omega^2\tau^2 \gg 1$ Small E_r

Corrections of field distortions: TPC90

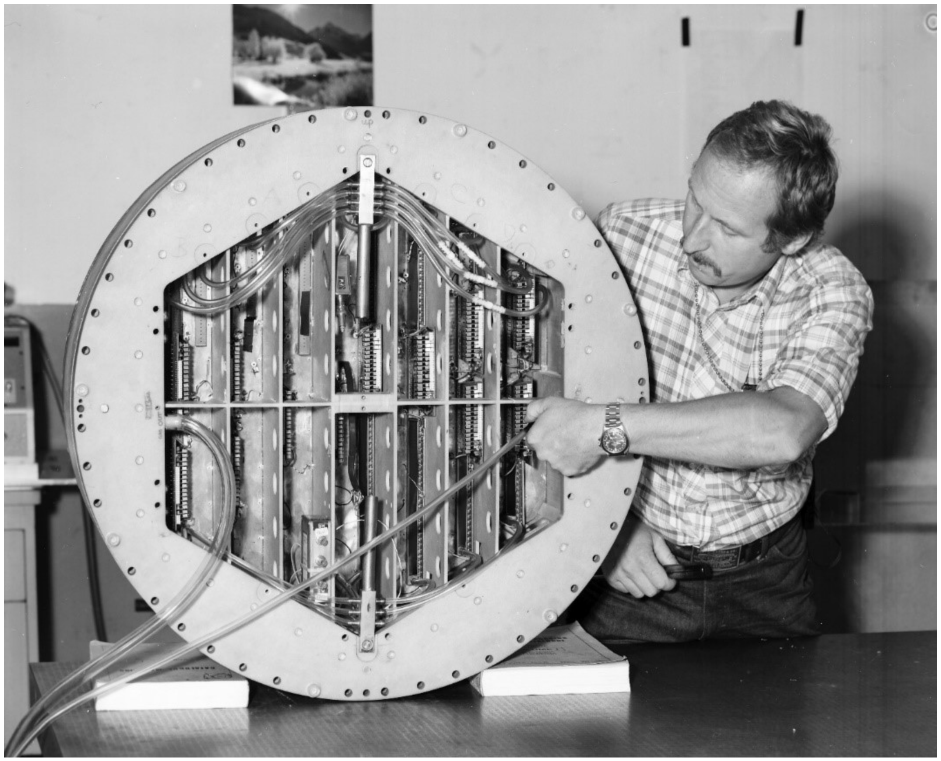
- The above concepts were well understood and were included in the April 1983 Technical Design Report
  - Of course an experimental proof and a proposal how to handle the distortions were necessary
- The LEPC defined as milestone the construction of a prototype
  - TPC90
    - $L_{\mathrm{D}} = 130$ cm
    - $\varnothing = 90$ cm
    - $E_{\mathrm{D}} = 110$ V/cm
    - $B_{\max} = 12$ kG
    - Laser MOPALITE 400
  - Prototypes of final sectors





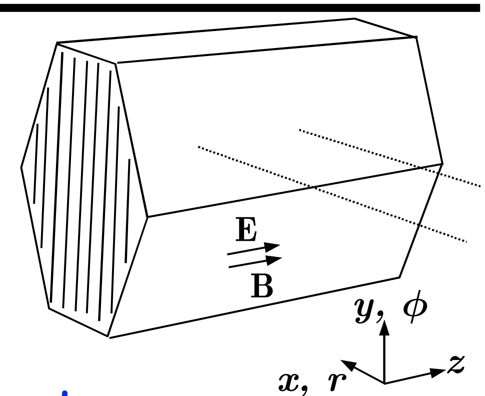


TPC90



Corrections of the E and B distortions

$$\mathbf{v}_d = \frac{\mu}{1+\omega^2\tau^2}\left[\mathbf{E} + \frac{\omega\tau}{B}\mathbf{E}\times\mathbf{B} + \omega^2\tau^2\frac{\mathbf{E}\cdot\mathbf{B}}{B^2}\mathbf{B}\right]$$



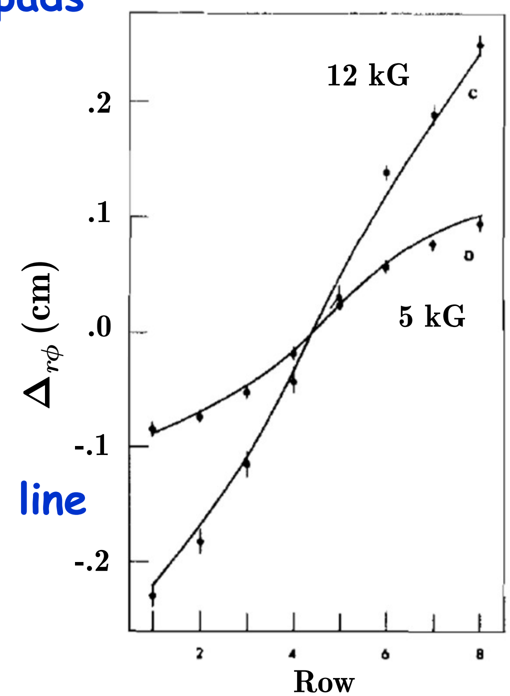
- Using TPC90 it was possible to verify:
  - That our model of the distortions was correct
  - That distortions were mostly caused by the magnetic field
- The ionization produced by the laser is measured by the pads
  - The azimuthal distortion is

$$\Delta_{r\phi} = \int_0^T v_{r\phi}\,dt = \int_z^0 \frac{v_{r\phi}}{v_z}\,dz$$

  - It is possible to prove that

$$\Delta_{r\phi} = \frac{\omega\tau}{1+\omega^2\tau^2}\int_z^0 \left(\frac{B_x}{|B_z|} - \frac{E_x}{E_z}\right)dz$$

- In the plot the points are the displacement of the measurements done with the pads from the laser straight line
- The lines are the computed $\Delta_{r\phi}$ based on B field maps
  - We concluded the contribution of the electric field radial distortions E_r was negligible



Design Status Report 1984

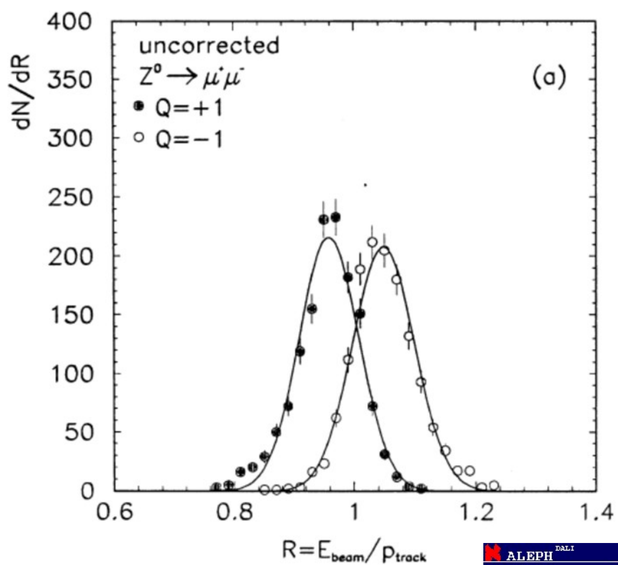
- All the described studies went in the 1984 Status Report
  - From the Status Report introduction …

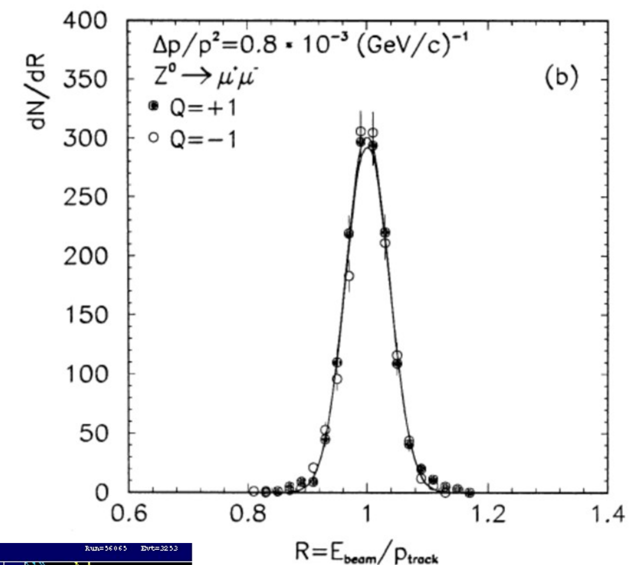
… Our status with respect to these milestones is as follows:

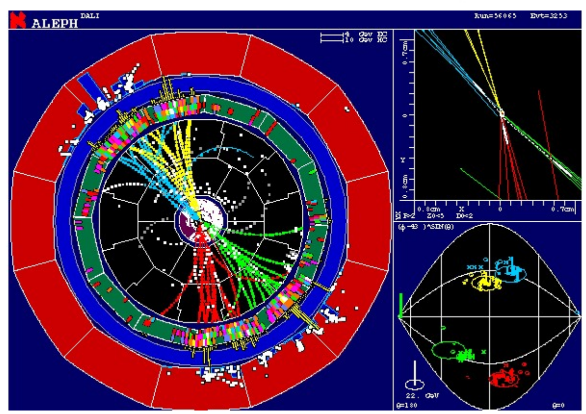
i) TPC90 is the name of our prototype TPC: It provides the possibility to drift 1.5 m but, because of cost, it accommodates only end sectors somewhat smaller than full-size. The magnetic field is pulsed to a maximum value of 12 kG. It is used as a facility for studying all parameters of TPC operation, using both laser tracks and cosmic rays. So far, all experiments have used a sector with 8 mm × 8 mm pads in straight rows. A new sector using 6 mm × 30 mm pads in circular rows is just about ready, and is scheduled to go into TPC90 in September. The value of these tests to the collaboration cannot be overestimated, especially the information gained with the help of the lasers. On the basis of these tests we are convinced that the TPC operation is well understood, and that a sagitta precision of 100 μm on stiff tracks will be obtained. The TPC is no longer the source of concern that it was before these tests were undertaken.

TPC Commissioning

- Performances of the TPC using 1989-1990 data
  - Before and after distortions corrections







The TPC group in years 83-84

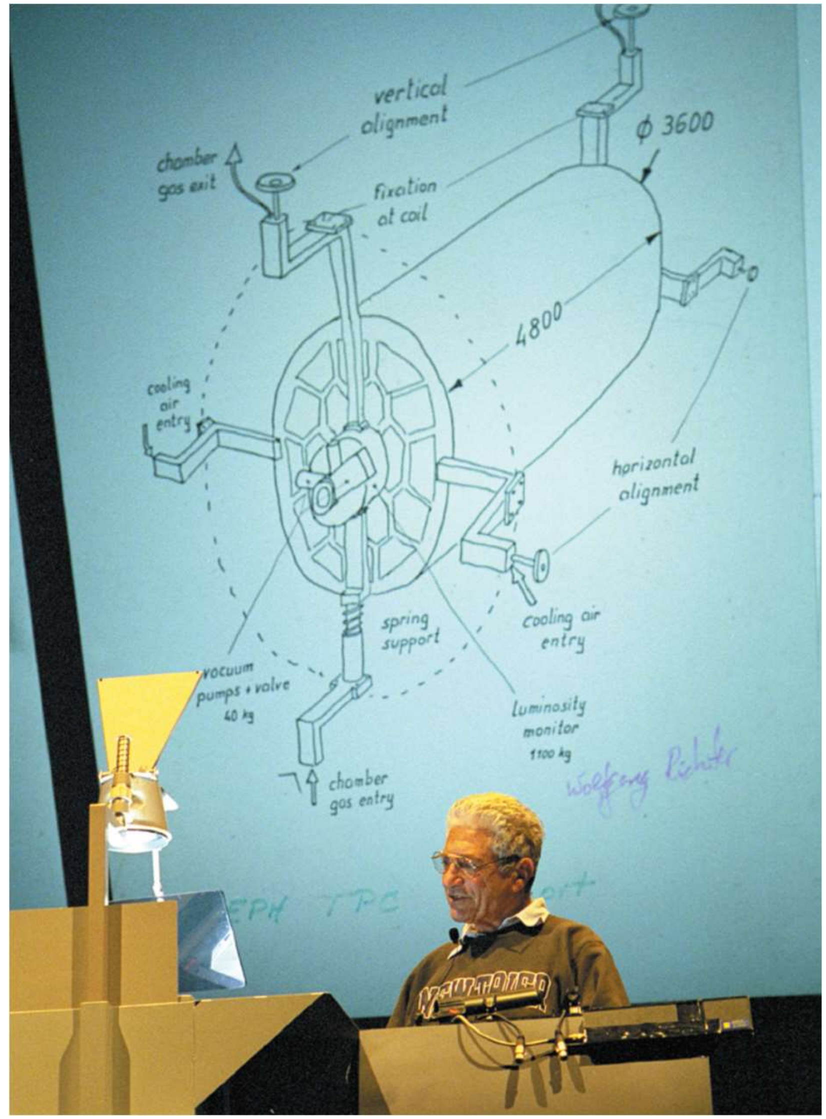
25 years of memories

- **In the book ALEPH Experience Jack remember the work of this period**

> … The question was pursued seriously by Francesco Ragusa and Gigi Rolandi. Within a few weeks they had come with a note, in which they quite clearly had achieved a clear understanding of the resolution errors associated with the drift of the electrons in the crossed electric and magnetic fields of the TPC, as well as the errors associated with the production of the signals on the pads of the wire chamber planes.

- **About the distortion studies he said**

> … One of the important outcomes of the Rolandi and Ragusa study had been the realization of the importance of the magnetic field as a stabilizer of the drift paths. I think that the happiest moment of my life in Aleph was listening, at our plenary meeting in November 1983, to the report by Julia Sedgbeer on these measurements, in which one after the other of these predictions were quantitatively confirmed.



50 Years with Gigi

If Jack said it …

… While preparing this talk all those memories
returned vividly

They are among the most beautiful remembrances of ALEPH

Thank you for listening and having given to me
the opportunity to share with you

Thank you Gigi: working with you has ben
a pleasure and an honor

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