

On the Magnetic-field Requirements for the LC TPC

OUTLINE of TALK

- Overview of the LC TPC
- Magnetic-field issue
 - The systematic uncertainty
 - The B-field Map for the LC TPC
- The Aleph B-Map
- Recommendations and Ideas

Preparing LC Note...

LC-DET-2005-XXX

On the Magnetic-field Requirements for a TPC at the Linear Collider¹

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...based on experience with Aleph TPC

HISTORY

1992: First discussions on detectors in Garmisch-Partenkirchen (LC92). Silicon? Gas?
1996-1997: TESLA Conceptual Design Report. Large wire TPC, 0.7Mchan.
1/2001: TESLA Technical Design Report. Micropattern (GEM, Micromegas) as a baseline, 1.5Mchan.
5/2001: Kick-off of Detector R&D
11/2001: DESY PRC proposal. for TPC R&D (European & North American teams)
2002: UCLC/LCRD proposals
2004: After I TRP,
WWS R&D panel
Europe
Chris Damerell (Rutherford Lab. UK)
Jean-Claude Brient (Ecole Polytechnique, France)
Wolfgang Lohmann (DESY-Zeuthen, Germany)

Asia
HongJoo Kim (Korean National U.)
Tohru Takeshita (Shinsu U., Japan)
Yasuhiro Sugimoto (KEK, Japan)

North America
Dan Peterson (Cornell U., USA)
Ray Frey (U. of Oregon, USA)
Harry Weerts (Fermilab, USA)

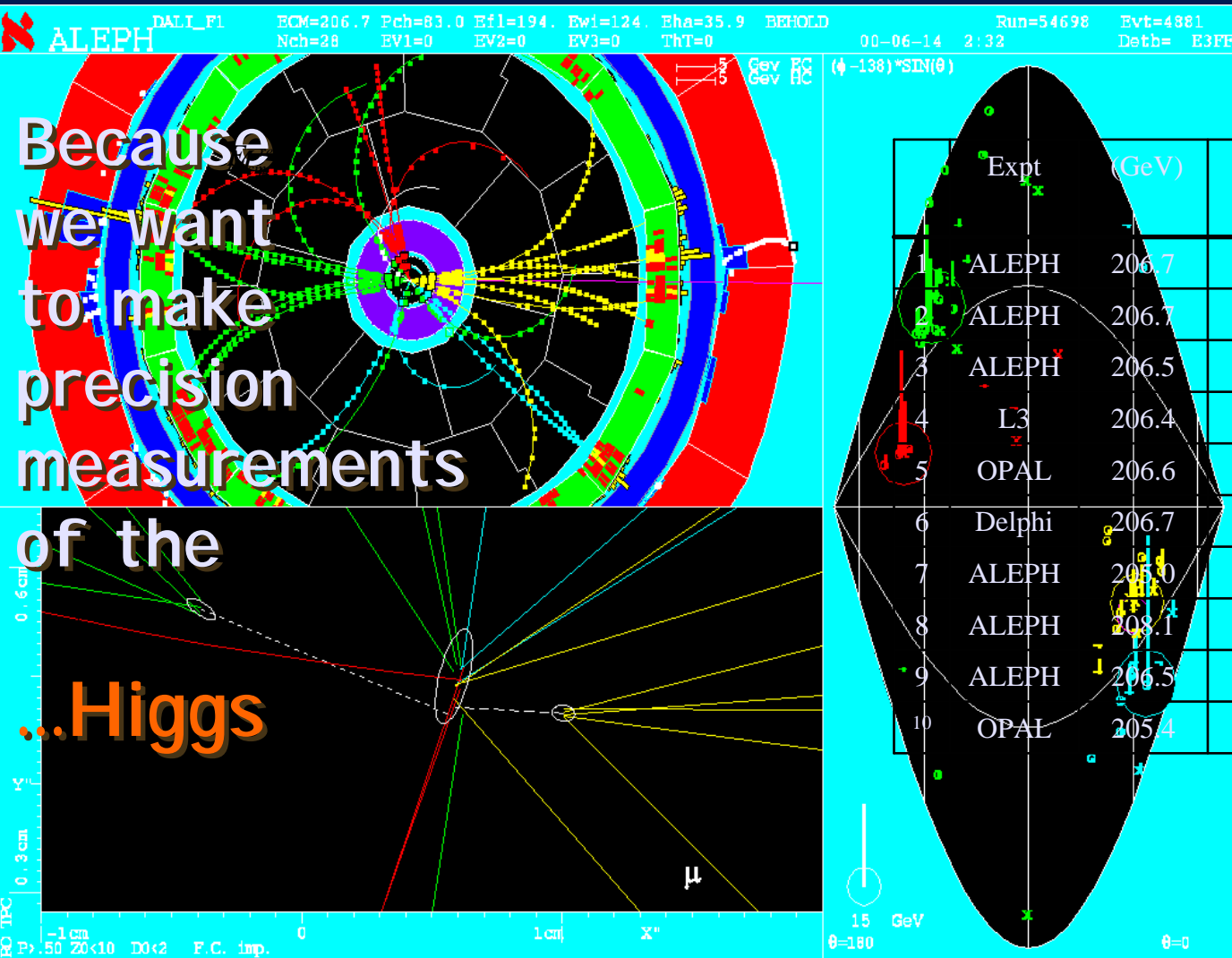
GOAL

To design and build an ultra-high performance

Time Projection Chamber

...as central tracker for the ILC detector, where excellent vertex, momentum and jet-energy precision are required

Motivation...



TPC R&D Groups

Europe

RWTH Aachen
DESY
U Hamburg
U Freiburg
U Karlsruhe
UMM Krakow
Lund/Stockholm
MPI -Munich
NIKHEF
BINP Novosibirsk
LAL Orsay
IPN Orsay
U Rostock
CEA Saclay
PNPI StPetersburg

America

Carleton U
Cornell/Purdue
LBNL
MIT
U Montreal
U Victoria

Asian I LC gaseous-tracking groups

Chiba U
Hiroshima U
Minadamo SU-IIT
Kinki U
U Osaka
Saga U
Tokyo UAT
U Tokyo
NRI CP Tokyo
Kogakuin U Tokyo
KEK Tsukuba
U Tsukuba

Other USA

MIT (LCRD)
Temple/Wayne
State (UCLC)
Yale

...OTHER?

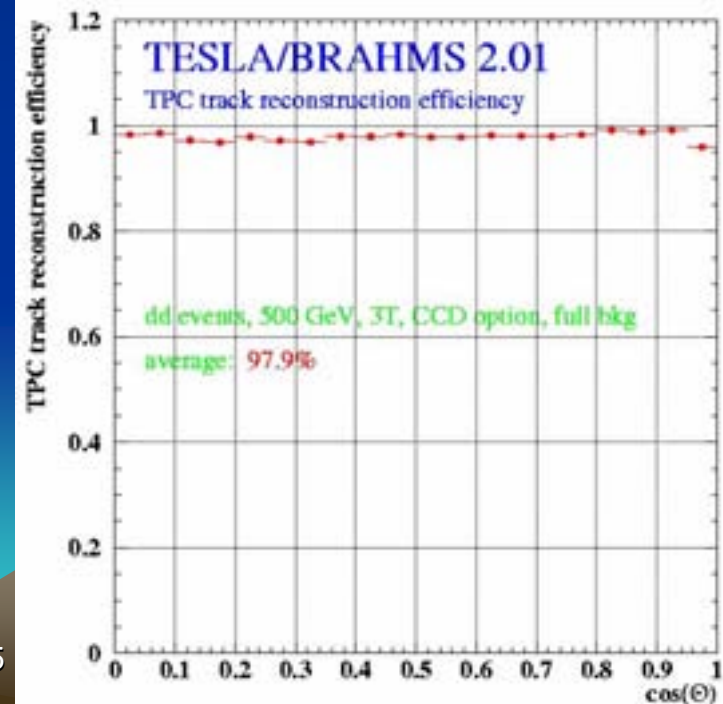
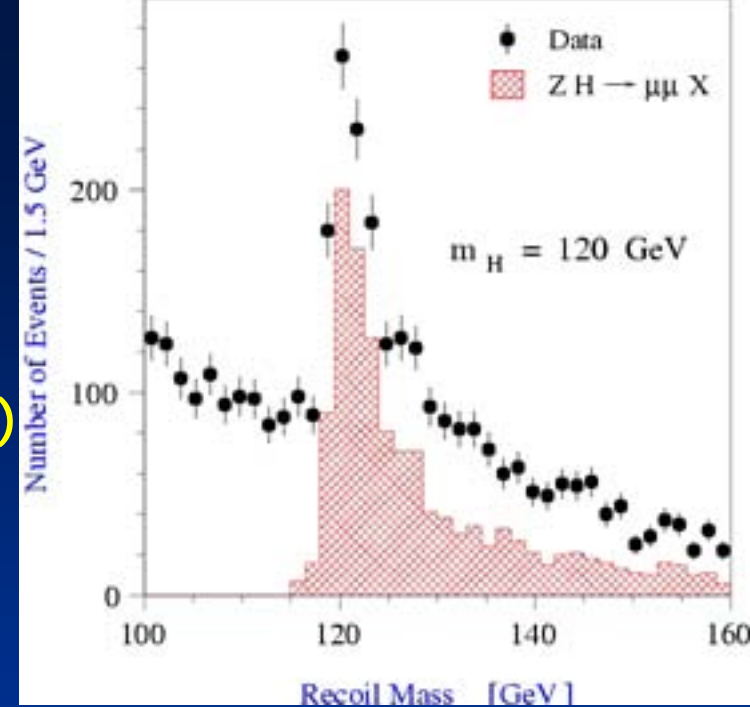
Physics determines detector design

★ momentum: $d(1/p) \sim 10^{-4}/\text{GeV}(\text{TPC only})$
 $\sim 0.6 \times 10^{-4}/\text{GeV}(\text{w/vertex})$
 (1/10xLEP)

$e^+e^- \rightarrow ZH \rightarrow \mu\mu X$ goal: $\delta M_{\mu\mu} < 0.1 \times \Gamma_Z$
 $\rightarrow \delta M_H$ dominated by beamstrahlung

★ tracking efficiency: 98% (overall)

excellent and robust tracking efficiency by combining vertex detector and TPC, each with excellent tracking efficiency

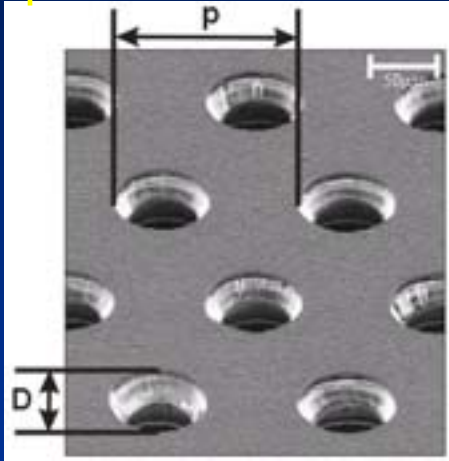


Motivation/Goals

- Continuous 3-D tracking, easy pattern recognition throughout large volume
- ~98% tracking efficiency in presence of backgrounds
- Timing to 2 ns together with inner silicon layer
- Minimum of X_0 inside Ecal (<3% barrel, <30% endcaps)
- $\sigma_{pt} \sim 100\mu\text{m}$ ($r\phi$) and $\sim 500\mu\text{m}$ (rz) @ 3 or 4T for right gas if diffusion limited
- 2-track resolution <2mm ($r\phi$) and <5-10mm (rz)
- dE/dx resolution <5% -> e/pi separation, for example
- Full precision/efficiency at 30 x estimated backgrounds

Gas-Amplification Systems: Wires & MPGDs→

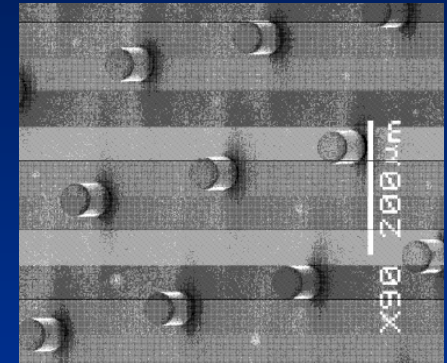
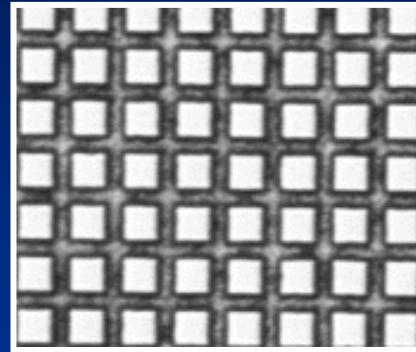
GEM: Two copper foils separated by kapton, multiplication takes place in holes, uses 2 or 3 stages



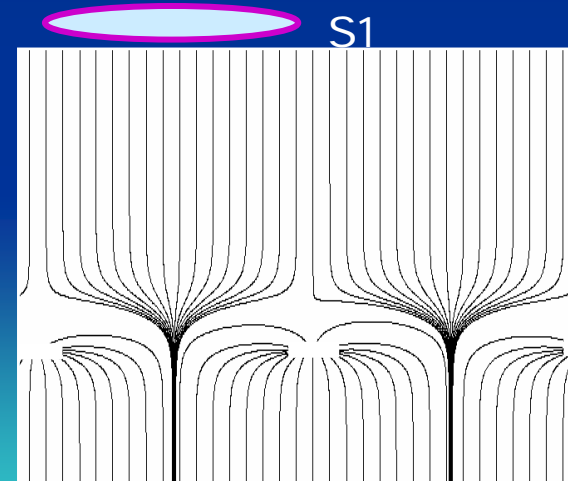
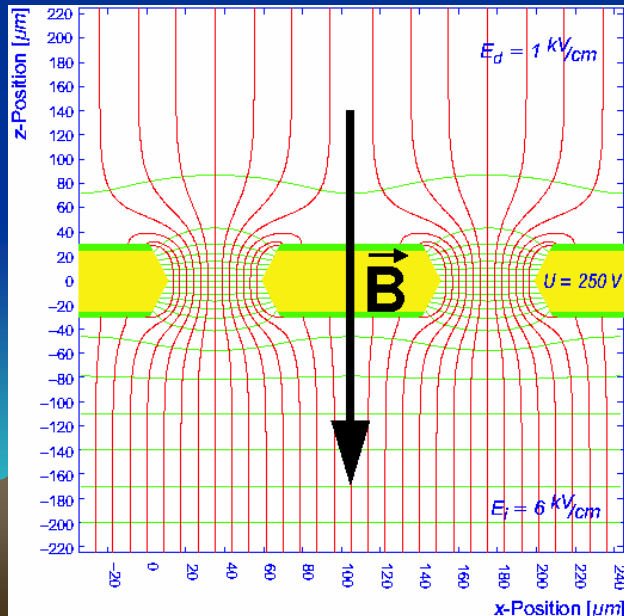
$P \sim 140 \mu\text{m}$

$D \sim 60 \mu\text{m}$

Micromegas: micromesh sustained by $50 \mu\text{m}$ pillars, multiplication between anode and mesh, one stage



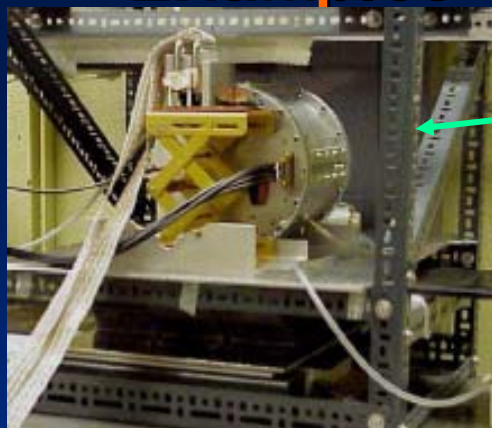
$S1/S2 \sim E_{\text{amplif}} / E_{\text{drift}}$



Ron Settles MPI-Munich/DESY
Snowmass2005 15-27 July 2005

S2

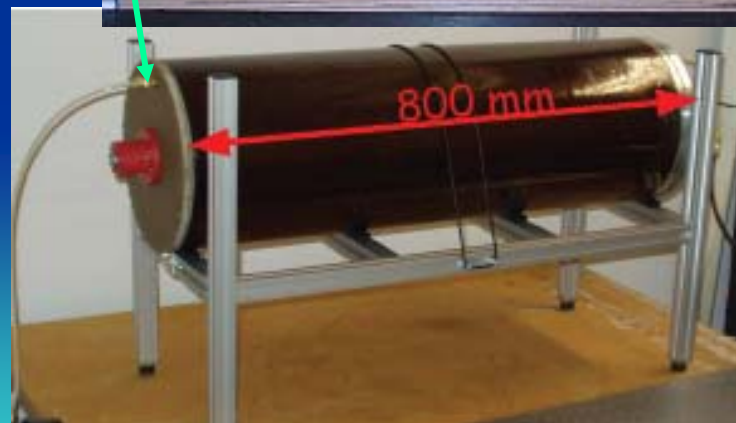
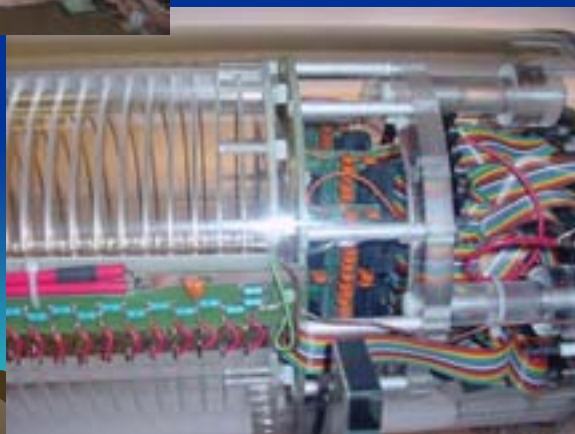
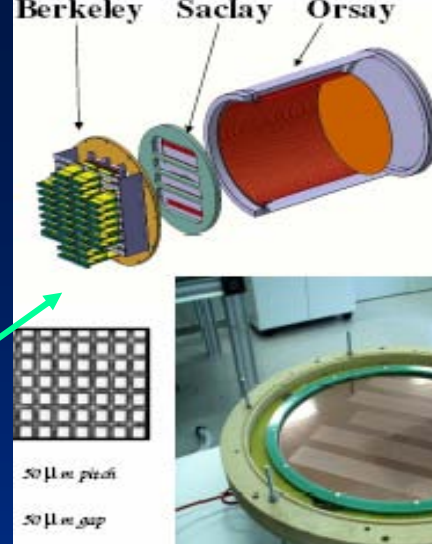
Examples of Prototype TPCs



Carleton, Aachen,
Cornell/Purdue, Desy (n.s.)
for B=0 or 1 T studies

Saclay, Victoria, Desy
(fit in 2-5 T magnets)

Karlsruhe, MPI / Asia,
Aachen built test TPCs
for magnets (not shown),
other groups built small
special-study chambers



Facilities



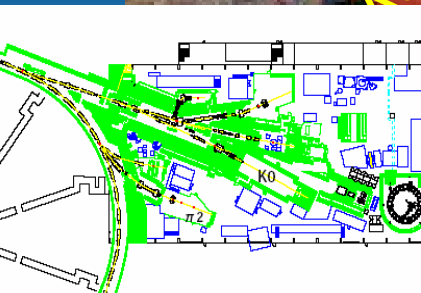
Desy 5T magnet,
cosmics, laser



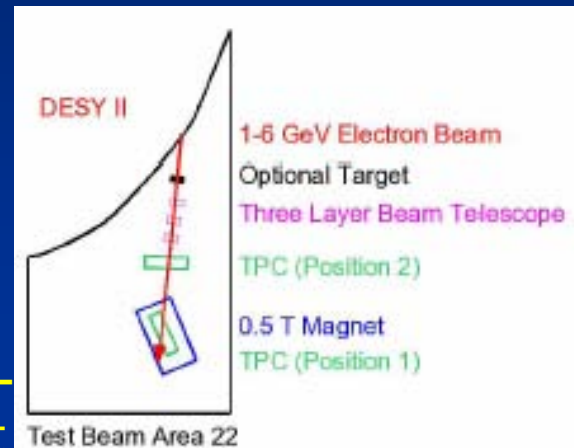
Saclay 2T magnet,
cosmics



Kek 1.2T, 4GeV
e⁺e⁻ test-beam



Cern test-
beam (not
shown)



Desy 1T, 6GeV e⁺
e⁻ test-beam

TPC R&D Summary

- Experience with MPGDs being gathered rapidly
- Gas properties rather well understood
- Diffusion-limited resolution seems feasible
- Resistive foil charge-spreading demonstrated
- CMOS RO demonstrated
- Design work starting

TPC central-tracker tasks

ISSUES

- Performance/Simulation
- Design
- Backgrounds, alignment, corrections

Performance/Simulation

- Momentum precision needed for overall tracking?
- Momentum precision needed for the TPC?
- Arguments for dE/dx , V^0 detection
- Requirements for
 - 2-track resolution (in $r\phi$ and z)?
 - track-gamma separation (in $r\phi$ and z)?
- Tolerance on the maximum endplate thickness?
- Tracking configuration
 - Calorimeter diameter
 - TPC
 - Other tracking detectors
- TPC outer diameter
- TPC inner diameter
- TPC length
- Required B-mapping accuracy in case of non-uniform B-field?

Design

- Gas-Amplification technology → input from R&D projects at Snowmass tracking session
 - Chamber gas candidates
- Electronics design: maximum density possible?
 - Zeroth-order “conventional-RO” design
 - Is there an optimum pad size for momentum, dE/dx resolution and electronics packaging?
 - Silicon RO: proof-of-principle
- Endplate design
 - Mechanics
 - Minimize thickness
 - Cooling
- Field cage design

Backgrounds/alignment/distortion-correction

- Revisit expected backgrounds
- Maximum positive-ion buildup tolerable?
- Maximum occupancy tolerable?
- Effect of positive-ion backdrift: gating plane?
- Tools for correcting space charge in presence of bad backgrounds?

The systematic uncertainty

Ron Settles / MPI-Munich
Frascati 2.11.98

TRACKING ALIGNMENT

REQUIREMENTS ON $\delta(\frac{1}{f_1})$

MODELS FOR DISTORTIONS

EXPERIENCE

THE CHALLENGE

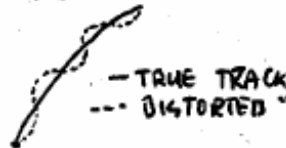
SYSTEMATICS

MODEL A

EACH MEAS. PT. HAS SYSTEMATIC ERROR δx_0 :

δx_0 's ARE "STATISTICAL"

$$\delta s_0 = \frac{1}{8} \sqrt{\frac{320}{N+5}} \delta x_0$$



If we require:

(i) $\delta s_0 = 0.1 \delta s \Rightarrow \delta x_0 \approx 0.1 \delta x \approx 10 \mu\text{m LC DET}$

or:

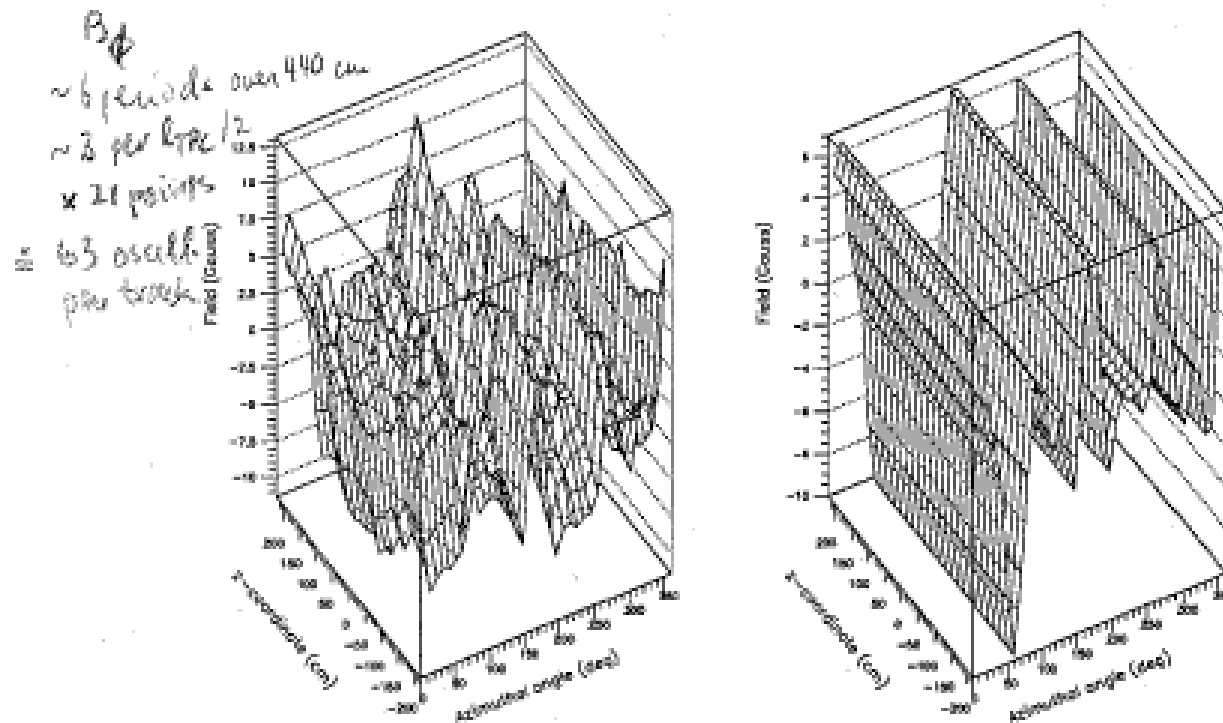
(ii) $\delta s_0 \oplus \delta s = 1.1 \delta s \Rightarrow \delta x_0 \approx 0.5 \delta x \approx 50 \mu\text{m LC DET}$

The systematic uncertainty

- So, I started writing this note assuming the linear model and $S_0 = 10\mu\text{m}$.
- When I showed an early draft to Dean, he said, “you should add them quadratically”
- And he was right



The systematic uncertainty



(c) Difference (Hall map - "Type I").

(d) Contribution from "Type IV" terms.

(θ denotes azimuthal angle in this paper)

Figure 8: Results for B_θ expansions. Each figure depicts B_θ on the $r = r_{\text{max}}$ radial surface as a function of z and θ .

Aleph Note by Steve Thorn: ALEPH 94-162, PHYSIC 94-138

The systematic uncertainty

From the Aleph experience, systematic effects for the TPC were understood to the $70\mu\text{m}$ level, as can be seen on p. 58 of [14]. Aleph was well understood in 1999, and the best possible tracking precision (calculated using the Aleph Monte Carlo) was $\delta(\frac{1}{p}) = 4.5 \cdot 10^{-4}(\text{GeV}/c)^{-1}$, whereas a value of $4.9 \cdot 10^{-4}(\text{GeV}/c)^{-1}$ is the average of the year-to-year resolution achievements. The difference in quadrature between these two numbers translates to a $\sim 70\mu\text{m}$ effect[15] which increased the TPC point resolution and can be considered as a measure of the understanding of corrections for systematic effects.

Using this as a guide and the fact that the LC TPC will have a better σ_{point} and more measured points than Aleph and allowing at most a 5% increase in the momentum error means that the systematic error on the point resolution should be below about $s_0 \simeq 30\mu\text{m}$ for the LC TPC (the symbol s_0 will be used for the tolerance).

Note that the final systematic error will include all corrections (detector alignment, distortions related to background, B-map accuracy, etc.). We shall use $30\mu\text{m}$ as an upper limit in the following for estimating accuracy of the B-field map.

The B-field

The 'standard' TPC requirement for the B-field homogeneity has been (from the LC Note):

$$\int \frac{B_r}{B_z} dz < h = 2\text{mm} \quad (1)$$

where h is the 'homogeneity' tolerance. Note that it is straight-forward to design the main LC-detector solenoid which satisfies this '2 mm condition', see e.g. [8, 13, 3].

The ILC machine design is presently being finalized[17] and is considering several options for magnetic elements in the inner region where the beams pass through the detector, which due to their stray B-fields in the TPC drift volume might cause Eq.1 to be violated. In particular, the LC Machine-Detector-Interface (MDI) panel[18] is asking in preparation for the Snowmass 2005 Workshop[19, 20], the following questions (among many others):

- The 20-mrad crossing angle geometry requires beam trajectory correction with a Detector Integrated Dipole (DID) as described in LCC-143[21]. Is this acceptable?
- Overlap of the solenoid field with the final focus quads requires an optics correction with an antisolenoid as described in LCC-142[22]. Is this acceptable?

The B-field

Distortion Corrections for the ALEPH TPC

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Cern, December 2001

1

http://wisconsin.cern.ch/~wiedenma/TPC/Distortions/CERN_LC.pdf

The B-field

- Compute distortions from Langevin equation

$$\vec{v} = \frac{\mu}{1 + (\omega \tau)^2} \left(\vec{E} + (\omega \tau) \frac{\vec{E} \times \vec{B}}{|\vec{B}|} + (\omega \tau)^2 \frac{\vec{B}(\vec{E} \cdot \vec{B})}{\vec{B}^2} \right)$$

Corrections exact if B-field known exactly; so what must B accuracy be?

$$\Delta \hat{r} \hat{\varphi}_E = \frac{1}{1 + (\omega \tau)^2} \int_z^{z_M} \left(\frac{E_\varphi}{E_z} - (\omega \tau) \text{sign}(B_z) \frac{E_r}{E_z} \right) dz ; \quad \Delta \hat{r}_E = \frac{1}{1 + (\omega \tau)^2} \int_z^{z_M} \left(\frac{E_r}{E_z} - (\omega \tau) \text{sign}(B_z) \frac{E_\varphi}{E_z} \right) dz ;$$

$$\Delta \hat{r} \hat{\varphi}_B = \frac{(\omega \tau)}{1 + (\omega \tau)^2} \int_z^{z_M} \left((\omega \tau) \frac{B_\varphi}{B_z} - \frac{B_r}{|B_z|} \right) dz ; \quad \Delta \hat{r}_B = \frac{(\omega \tau)}{1 + (\omega \tau)^2} \int_z^{z_M} \left((\omega \tau) \frac{B_r}{B_z} - \frac{B_\varphi}{|B_z|} \right) dz ;$$

The relevant equations for movement of drifting electrons in B-field

From the LC Note...

The relevant equations for the movement of drifting electrons due to the B-field can be derived from Eq.2 (see p.16 of [14]),

$$\Delta r_{\varphi} = \frac{(\omega\tau)}{1 + (\omega\tau)^2} \int_z^{z_{max}} \left((\omega\tau) \frac{B_{\varphi}}{B_z} + \frac{B_r}{B_z} \right) dz \quad (3)$$

and

$$\Delta r = \frac{(\omega\tau)}{1 + (\omega\tau)^2} \int_z^{z_{max}} \left((\omega\tau) \frac{B_r}{B_z} - \frac{B_{\varphi}}{B_z} \right) dz. \quad (4)$$

Taking the first term of Eq.4, assuming $\omega\tau$ to be large, approximating the integral by $\Delta r \simeq \frac{B_r}{B_z} \ell_{drift}$ with $\ell_{drift} = z_{max} - z$ and approximating $\frac{B_r}{B_z} \simeq \frac{h}{\ell_{TPC}}$, then $\Delta r = \int_z^{z_{max}} \frac{B_r}{B_z} dz = h \frac{\ell_{drift}}{\ell_{TPC}}$. Differentiating both sides to calculate the error the usual way and setting $\delta(\Delta r) = s_0$ [23], then $\delta(\frac{B_r}{B_z}) \simeq \frac{\delta h}{\ell_{TPC}} \simeq \frac{s_0}{\ell_{drift}}$. The same exercise for the second term of Eq.4 yields $\frac{1}{\omega\tau} (\frac{B_{\varphi}}{B_z} \ell_{drift}) = s_0$ or $\delta \frac{B_{\varphi}}{B_z} = \omega\tau \frac{s_0}{\ell_{drift}}$. The effect of this component is mitigated by $\omega\tau$ for the Δr movement and can be neglected since $\omega\tau$ will be large.

For the case of the $r\varphi$ coordinate, Eq.3, the roles of B_r and B_{φ} are interchanged. The most stringent conditions then from Eqs.3 and 4 are given by[24]

$$\delta \frac{B_r}{B_z} \simeq \delta \frac{B_{\varphi}}{B_z} \simeq \frac{\delta h}{\ell_{TPC}} \simeq \frac{s_0}{\ell_{drift}}. \quad (5)$$

The estimation for the accuracy needed for the $B_{r,\varphi}$ components from Eq.5 is, since $B_z \gg B_r$,

$$\frac{\delta B_{r,\varphi}}{B_z} \simeq \frac{\delta h}{\ell_{TPC}} \simeq \frac{s_0}{\ell_{drift}}. \quad (6)$$

It is important to remember that the value $\delta B_{r,\varphi}$ is the residual uncertainty of the positive and negative fluctuations of the $B_{r,\varphi}$ after integrating over the drift path of the electron cloud for each point and over the points along a track.

For the right side expression for the tolerance in Eq.6, the field homogeneity

From the LC Note...

the electron cloud for each point and over the points along a track.

For the right side expression for the tolerance in Eq.6, the field homogeneity cancels out and it depends only on the systematic point-resolution tolerance s_0 and the drift distance. For example, the tolerance is $\frac{s_0}{\ell} \simeq 1.5 \times 10^{-5}$ for $s_0 = 30\mu\text{m}$ and

$\ell_{\text{drift}} = 2000$ mm. If $B_z = 40,000$ G, then the integral of the r and φ components over the drift paths of the electrons for each point and over the points along a track should lead to a residual uncertainty of ~ 1 G. The requirement will be relaxed for shorter drift distances; realistic simulations must be performed to determine more accurate values than these back-of-the-envelope estimates.

The relative field homogeneity $\frac{\delta h}{h} \simeq \frac{s_0}{h} \frac{\ell_{\text{TPC}}}{\ell_{\text{drift}}}$ must be known to 1.5 permille for $\ell_{\text{drift}} = \ell_{\text{TPC}}$ and $s_0 = 30\mu\text{m}$ if the effect of the DID[21] and/or antisolenoid[22] is $h = 20$ mm (Eq.1) in the TPC volume[25].

The Aleph B-map...

main reason for this is contained in a sentence from the article on Tracking Alignment by Alain Bonissent:

“The magnetic field measurements were made in a very short period during the first mounting of Aleph, and the experimental conditions were not ideal. After the complete assembly, such measurements could never be repeated, so that this will remain forever as an uncertainty.”



Hall probe measuring devices being set up in the coil

From the LC Note...

4.1 The Aleph B-field Map

The goal of Aleph B-field map was to be internally self-consistent to an accuracy of $\frac{\delta B}{B} \simeq 1 \times 10^{-4}$, according to [3], for the magnet configuration (i.e., main-coil current \leftrightarrow correction-coil currents) which was set during mapping. This map verified[3] that the '2mm condition' of Eq.1 was satisfied for all components of the Aleph B-field.

However 1×10^{-4} was not achieved. The standard deviation, σ_{map} , between measurements and the fit of a model derived from Maxwell's equations, for the Aleph B-map after corrections (see below) was 0.3 G for B_z and ~ 6 G for the B_r and B_ϕ [26], which corresponds to 5×10^{-4} or 0.5 permille. The residual uncertainty after integrating over the drift distances of the points for a track was $\frac{\sigma_{map}}{\sqrt{N_{map}}}$ where N_{map} was the number of fluctuations between measurements and map for the B-field. Typically N_{map} was about 60 for Aleph (Fig.8 in [26]) so that the residual error was < 1 G.

One problem with the Aleph B-field map was that the configuration used for

- Problems:
- Different coil configuration between mapping and running
 - Hall plate drifts
 - Temperature drifts

\Rightarrow Aleph should have taken more time for the calibration of various effects and mapped with more configurations.

B-field Map for the LC TPC

Aleph map almost good enough for the LC TPC; profit from experience:

- Map to better than 0.5‰ internal consistency; lay out for 0.1‰ to achieve this.
- Construct main detector coil to adhere to '2mm condition' if affordable.
- Establish to
 - The Hall plate calibration.
 - The number of Hall plates and NMR probes.
 - The position accuracy of the probes and mapping gear.
 - The number of positions per map.
 - The stability of power supplies, monitoring devices, etc.
- Do same for stray fields of MDI magnets.
- Mount matrix of Hall plates on LCTPC to monitor/check while running.
- Devise model including all material to compare with Hall-plate matrix.

The B-field

5 Summary

The work by a global group of institutes has goal of coordinating important R&D needed to design a continuous-tracking, high-performance TPC with the finest granularity, which is robust in high backgrounds, has a minimum of material and can keep residual systematic effects below $30\mu\text{m}$.

The answer to the MDI questions on the DID[21] and antisolenoid[22] is that the B-field map for the LC TPC will be good enough to meet the tracking requirements in any case. But we would like to know how large the effects of [21] and [22] are from the MDI group in order to calculate Eq.1 for them.