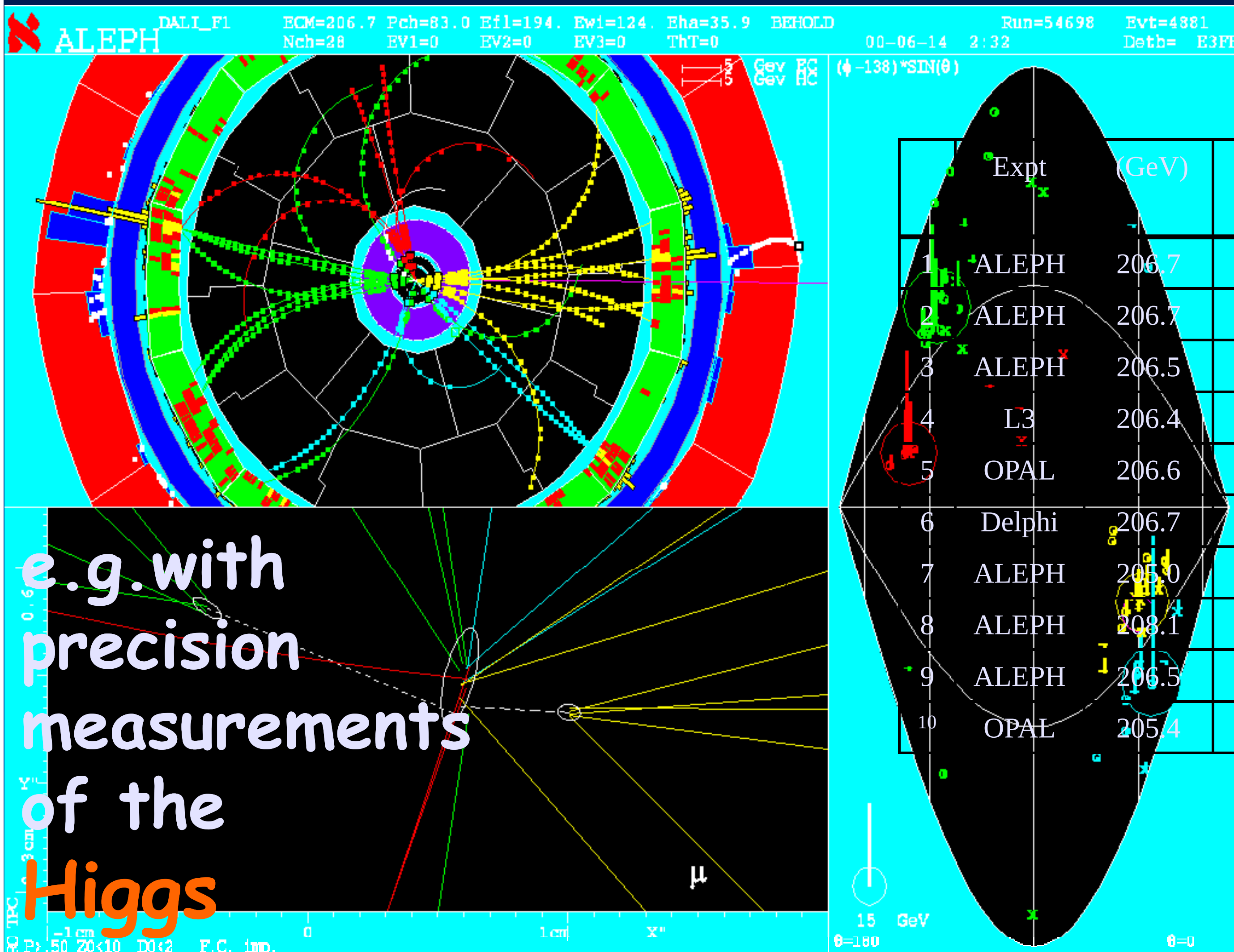
On the Magnetic-field Requirements for the LC TPC

OUTLINE of TALK

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

Goal: to revisit the Higgs…



e.g.with precision measurements of the **Higgs**

	Expt	(GeV)	Decay Channel	(GeV/c^2)	ln(1+s/b) 115 GeV/c^2
1	ALEPH	206.7	4-jet	114.3	1.73
2	ALEPH	206.7	4-jet	112.9	1.21
3	ALEPH	206.5	4-jet	110.0	0.64
4	L3	206.4	E-miss	115.0	0.53
5	OPAL	206.6	4-jet	110.7	0.53
6	Delphi	206.7	4-jet	114.3	0.49
7	ALEPH	205.0	Lept	118.1	0.47
8	ALEPH	208.1	Tau	115.4	0.41
9	ALEPH	206.5	4-jet	114.5	0.40
10	OPAL	205.4	4-jet	112.6	0.40

On the Magnetic-field Requirements for the LC TPC……

STATUS OF DISCUSSION

- Dan Peterson and I presented two different viewpoints at an LDC meeting at Snowmass05.
- Both of these viewpoints are based on simplified arguments to help understand the effects.
- Here are mine: "back-of-the envelope" must be done carefully.
- Christian Grefe is analyzing the field map for the LP which will be testing some of these ideas.
- Simuation work can help understand more details of the issue.

Prepared LC Note at Snowmass05 time…

LC-DET-2008-XXX

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

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DRAFT 2008-03-07

Is being updated now

Abstract

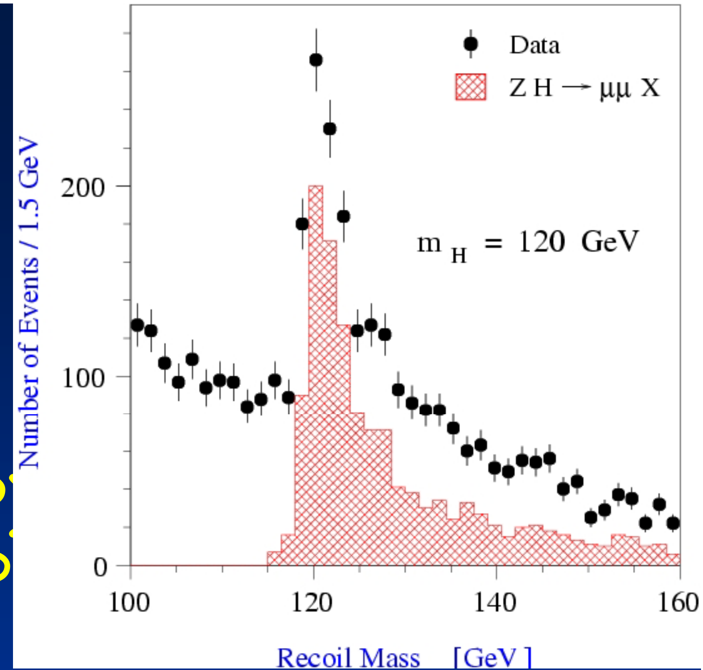
…based on experience with Aleph TPC

Physics determines detector design

★ **momentum: d(1/p) ~.9x10^{-5}/GeV (TPC only)**

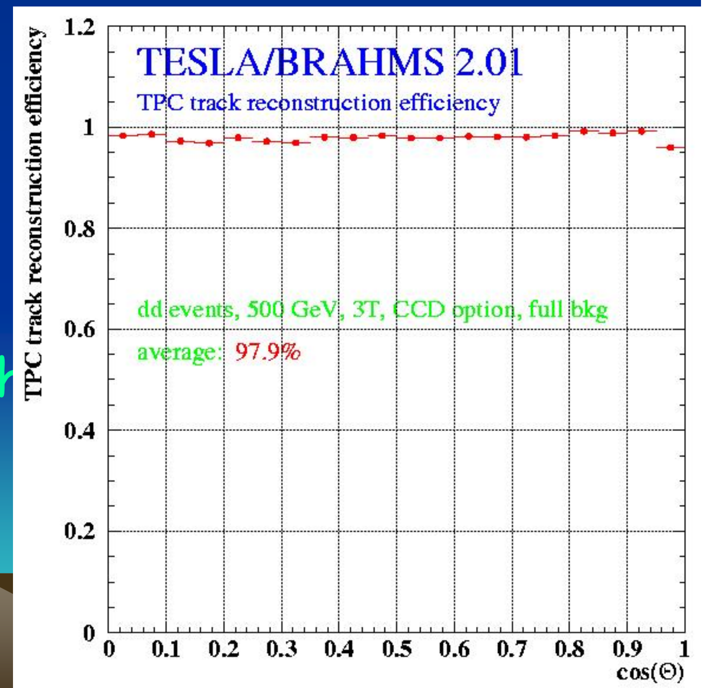
~ .3x10^{-5}/GeV(w/IP) (1/10xLEP

$e^+e^- \rightarrow ZH \rightarrow ll\ X$ goal: $\delta M \sim 20$MeV



★ **tracking efficiency: 98% (overall)**

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



TPC central-tracker tasks

ISSUES

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

Snowmass05 list of performance/simulation issues is being revisited for the ILD optimization

- Momentum precision needed for overall tracking?
- Momentum precision needed for the TPC?
- Arguments for dE/dx, V° detection
- Requirements for
  - 2-track resolution (in rφ and z)?
  - track-gamma separation (in rφ 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?

Performance: LC Note LC-DET-2007-005

Table 1: Performance goals and design parameters for a TPC with standard electronics at the ILC detector.

Size (LDC–GLD average)	ϕ = 3.6m, L = 4.3m outside dimensions
Momentum resolution (B=4T)	$\delta(1/p_t) \sim 10 \times 10^{-5}$/GeV/c TPC only; × 0.4 incl. IP
Momentum resolution (B=4T)	$\delta(1/p_t) \sim 3 \times 10^{-5}$/GeV/c (TPC+IT+VTX+IP).
Solid angle coverage	Up to at least $\cos\theta \sim 0.98$
TPC material budget	$< 0.03X_0$ to outer fieldcage in r
	$< 0.30X_0$ for readout endcaps in z
Number of pads	$> 1\times10^6$ per endcap
Pad size/no.padrows	~ 1mm×4–6mm/~200 (standard readout)
$\sigma_{singlepoint}$ in $r\phi$	~ 100μm (for radial tracks, averaged over driftlength)
$\sigma_{singlepoint}$ in rz	~ 0.5 mm
2-hit resolution in $r\phi$	< 2 mm
2-hit resolution in rz	< 5 mm
dE/dx resolution	< 5 %
Performance robustness	> 95% tracking efficiency for all tracks–TPC only)
(for comparison)	(> 95% tracking efficiency for all tracks–VTX only)
	> 99% all tracking[13]
Background robustness	Full precision/efficiency in backgrounds of 1% occupancy
	(simulations estimate < 0.5% for nominal backgrounds)
Background safety factor	Chamber will be prepared for 10 × worse backgrounds
	at the ILC start-up.

w/ MPGD!

The systematic uncertainty

Ron Settles /MPI-Munich
Frascati 3.11.98

TRACKING ALIGNMENT

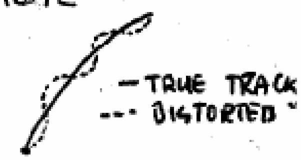
- REQUIREMENTS ON $\delta(\frac{1}{P_t})$
- MODELS FOR DISTORTIONS
- EXPERIENCE
- THE CHALLENGE

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) $\delta s_0 = 0.1\,\delta s \Rightarrow \delta x_0 \approx 0.1\,\delta x \simeq 10_{\mu m}$ LC DET

or:

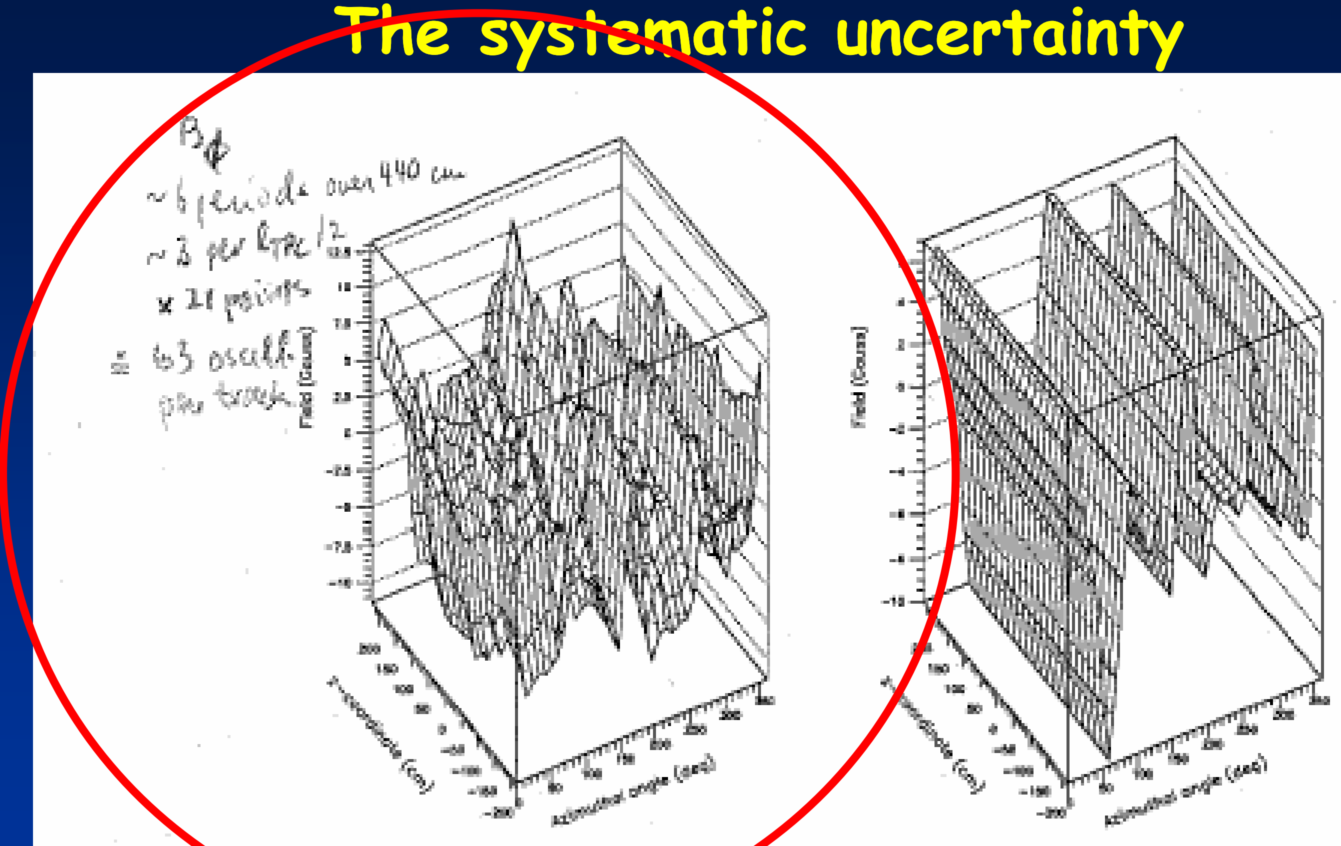
(ii) $\delta s_0 \oplus \delta s = 1.1\,\delta s \Rightarrow \delta x_0 \approx 0.5\,\delta x \simeq 50_{\mu m}$ LC DET

The systematic uncertainty

- So, I started writing this note aggressively assuming the linear model and $\delta x_o \equiv \delta\sigma_o = 10\mu m$.
- When I showed an early draft to Dean, he said, "you should add them quadratically"
- This is correct as you see next…

→→→

The systematic uncertainty



(c) Difference (Hall map − "Type I"). (d) Contribution from "Type IV" terms.

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

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

The B-field

Distortion Corrections for the ALEPH TPC

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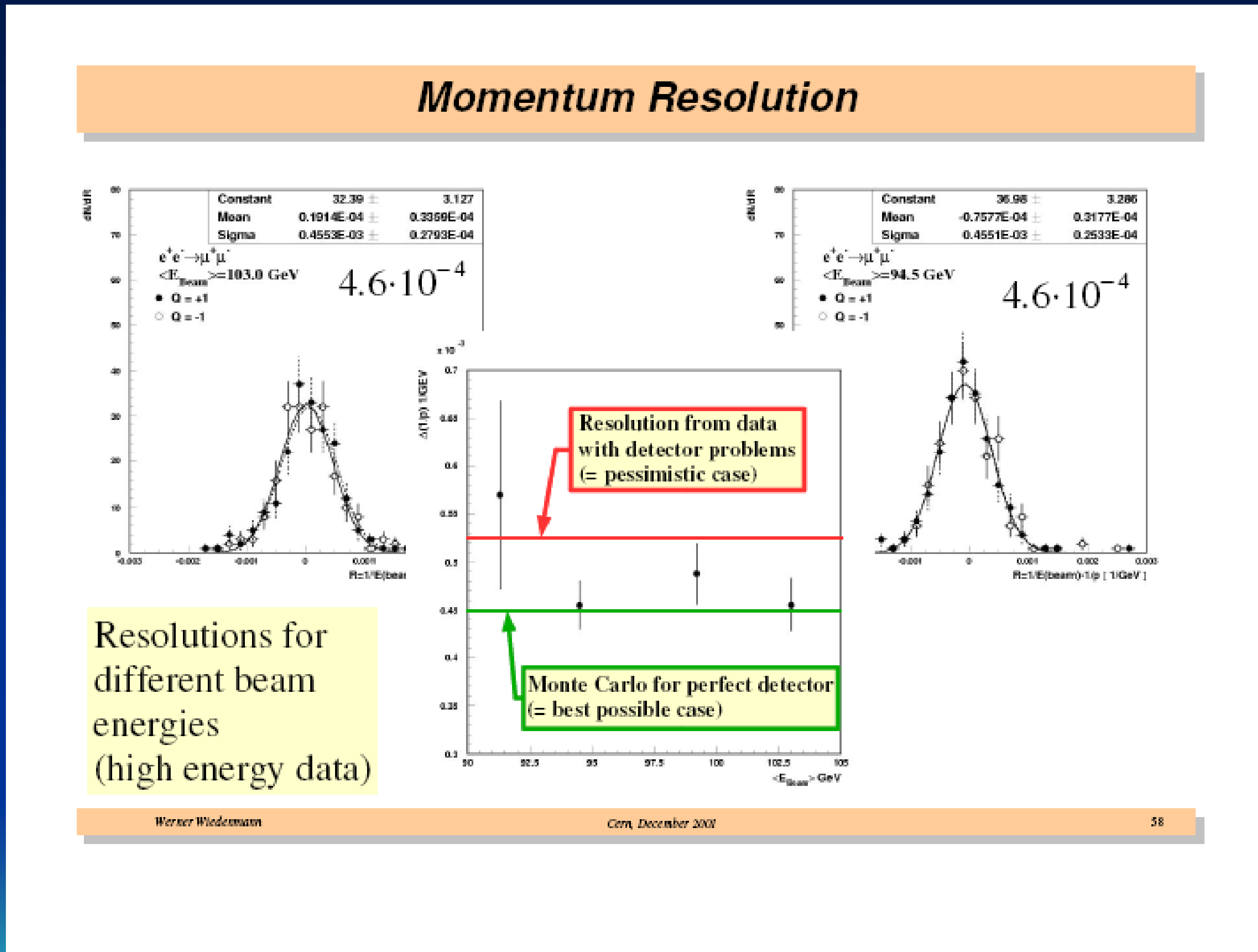
Werner Wiedenmann | *Cern, December 2001* | 1

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

The B-field



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

The systematic uncertainty

From the Aleph experience, systematic effects for the TPC were corrected to the 35–70μm 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 $\delta(\frac{1}{p}) = 4.5 \cdot 10^{-4}(\mathrm{GeV/c})^{-1}$, and values of $4.6 - 4.9 \cdot 10^{-4}(\mathrm{GeV/c})^{-1}$ were the year-to-year resolution achievements. The difference in quadrature between best-possible and achieved numbers translate to a 35-to-70 μm 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 $\sigma_0 \simeq 30$ μm for the LC TPC. The symbol σ_0 will be used for this tolerance.

Note that the final systematic error will include all corrections (detector alignment, distortions related to background, B-map accuracy, etc.). In the following we shall use 30 μm as an upper limit for estimating accuracy needed for the B-field map.

The B-field

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

- 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?

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

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

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

The B-field

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

In the past the "standard" TPC requirement for B-field uniformity has been the integral over the drift length

$$\int_{z}^{z_{max}} \frac{B_r}{B_z} dz < h = 2\mathrm{mm} \tag{1}$$

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?

From the LC Note…

The drifting electrons are governed by the Langevin equation

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

where μ $(= e\tau/m)$ is the electron mobility, ω $(= eB/m)$ is the cyclotron frequency and τ is the mean drift time between two collisions with gas molecules. *In principle if the B-field map is known to infinite precision, its effect can be corrected exactly using Eq.2.* To what accuracy, then, must the B-field be mapped so that the corrections can allow the momentum resolution to be maintained?

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]),

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

and

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

We shall now give some back-of-the-envelope reflections to estimate the B-mapping accuracy needed. Also it will be important for the LC TPC groups to choose a gas with large $\omega\tau$ so that the drifting electrons follow the magnetic field lines, which can be measured well, and minimize the effects of the space charge, which is not easy to measure, on the TPC performance. We assume $\omega\tau \simeq 20$ in the following.

From the LC Note...

Starting with the first term of Eq. 3, 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 $\frac{B_r}{B_z} \simeq \frac{h}{\ell_{TPC}}$ (from Eq. 1) then $\Delta r \simeq \int_z^{z_{max}} \frac{B_r}{B_z} dz \simeq h\frac{\ell_{drift}}{\ell_{TPC}}$. Differentiating both sides to calculate the error in the usual way, then $\delta(\frac{B_r}{B_z}) \simeq \frac{\delta h}{\ell_{TPC}} \simeq \frac{\delta(\Delta r)}{\ell_{drift}}$, or $\delta(\Delta r) = \delta h$ for the maximum drift. The same exercise for the second term of Eq.3 yields $\frac{1}{\omega\tau}(\frac{B_\varphi}{B_z}\ell_{drift}) \simeq \delta(\Delta r)$ or $\delta\frac{B_\varphi}{B_z} \simeq \omega\tau\frac{\delta(\Delta r)}{\ell_{drift}}$. Thus the requirement on this component is mitigated by a factor $\omega\tau$ for the Δr movement and can be neglected since $\omega\tau$ will be large. This is confirmed in practice [3], where the influence of B_φ has been measured to be an order of magnitude smaller than that of B_r.

For the case of the $r\varphi$ coordinate, comparison of Eqs. 3 and 4 shows that

$$\Delta r\varphi = \frac{\Delta r}{\omega\tau}. \qquad (5)$$

The measurement $r\varphi$ is critical for the stiff tracks so that the main requirement is

$$\delta(\Delta r\varphi) = \sigma_0. \qquad (6)$$

The estimation for the accuracy needed for the B_r component is, since $B_z >> B_r$,

$$\frac{\delta B_r}{B_z} \simeq \omega\tau\frac{\delta h}{\ell_{TPC}} \simeq \omega\tau\frac{\sigma_0}{\ell_{drift}} \simeq \omega\tau\frac{\sigma_0}{\ell_{TPC}}, \qquad (7)$$

the latter for $\ell_{drift} = \ell_{TPC}$. It is important to remember that the value δB_r is the residual uncertainty of the positive and negative fluctuations of the B_r after integrating over the drift path of the electron cloud for each point and over the points along a track.

From the LC Note…

For example, the tolerance for the $\Delta r\varphi$ correction is $\omega\tau\frac{\sigma_0}{\ell_{TPC}} \simeq 3\times10^{-4}$ for $\sigma_0 = 30\mu$m, $\omega\tau = 20$ and ℓ_{TPC} =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 ~ 10 G. If the most stringent tolerance is used for the Δr movement $\frac{\sigma_0}{\ell_{TPC}} \simeq 1.5\times10^{-5}$ for $\sigma_0 = 30\mu$m and ℓ_{TPC} =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.

Thus the field must be known to a residual uncertainty of between 1 G and 10 G from these examples. This accuracy was achieved in Aleph [25]. Realistic simulations must be performed to determine more accurate values than these back-of-the-envelope estimates.

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 quite 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 $\sim$ 6 G for the B_r and B_φ[25], which corresponds to 5×10^{-4}. 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 [25]) 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 ILD

Aleph map-accuracy good enough for the LC TPC, be we can profit from experience and do better:

- Lay out map to achieve better than 0.2‰ as was originally planned in Aleph.
- Construct main detector coil to adhere to ‘2mm condition’.
- Establish tolerances with careful simulation:
  - 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.