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The Linear Collider TPC: Revised Magnetic-field Requirements [*]

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Abstract

A Time Projection Chamber is being developed as central tracker for a detector at the International Linear Collider. The LCTPC has to perform better and to face more complicated event topologies and higher backgrounds than TPCs at previous e^+e^- colliders: this puts additional requirements on the overall system design. At present the technical design of the ILC machine is considering the use of special magnetic-field elements to guide the beams as they pass along the axis of the detector. Since the B-fields from such elements affect the TPC volume, the present note revisits the requirements on the magnetic field for the LCTPC. It is proposed to replace the original requirement on the homogeneity of the B-field by one on the accuracy of the B-field map. The purpose of this study is to achieve the best possible momentum resolution for the TPC, and it is demonstrated that the goal for the Aleph B-map accuracy is also sufficient for the LCTPC. Simulations should be made to cross-check these ideas and results communicated via memos or notes.[1]

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[1] A draft of this note was originally written at Snowmass2005[1][2]. The description of machine issues has been updated due to progress in the meantime. The original discussion on the TPC B-field has been revised considerably here. In particular we decided not, as in the original draft, to use back-of-the-envelope models to estimate the effects, because of their approximate nature leading to not-so-clear conclusions, but instead to employ real results from Aleph to derive the requirements for the LCTPC.

1 Introduction

The motivation for a TPC as tracker for a linear collider detector is described in the LC Note LC-DET-2002-008 and in the recent update LC-DET-2007-005 [3]. The main advantages are ease of pattern recognition with continuous 3-D tracking over a large volume containing a small amount of material, excellent momentum resolution and particle identification via dE/dx which will enhance topological event selection capabilities and improve identification of e/π jet components in the calorimeters. The main challenge for the LCTPC is to build a detector which performs 10 times better than at LEP, which is robust in high backgrounds and which is designed in such a way that systematic effects from distortions can be corrected to better than 30μm over the whole volume.
Technical issues relevant for the LCTPC were described in [3]. An R&D program to address them was outlined with regular updates [4][5].
Since at the ILC magnetic elements near the IP will affect the B-field uniformity, the B-field requirements for the TPC must be revised. Based on experience with the Aleph TPC [6][7], the requirements on the accuracy of the magnetic-field map for the LCTPC will be studied here. It will be shown that the accuracy achieved at Aleph when extrapolated to the LCTPC will be adequate after certain problems are avoided. This discussion leads to suggestions for the LCTPC B-field mapping procedure and for continuation of this study.

2 Overview

One of the main LCTPC R&D objectives is to study the new micropattern gas-detector technologies (MPGD), Gas Electron Multiplier [8] and Micromegas [9] which are attractive candidates for the readout planes since they promise to provide a better resolution and to avoid certain drawbacks of the MWPC technology. Development work is being pursued on all aspects of the TPC [3][5], on the amplification and the ion-suppression schemes, on the integration of high-density front-end electronics and on the mechanical issues related to the design of the field cage and the thin endplates. Another objective is the study of a "pixel" TPC based on CMOS pixel sensors to register signals from an MPGD [5][10].
The overall design of an ILC detector has been presented on several occasions [11]; also a detector for CLIC with TPC central tracker has been studied [12]. Important for the present note is the goal for the desired momentum precision in LC-DET-2007-005: $\delta p_t/{p_t}^2 \sim 10^{-4}$/GeV/c (TPC only) and $\delta p_t/{p_t}^2 \sim 3 \cdot 10^{-5}$/GeV/c (overall tracking). Whereas these values are based on a TPC rϕ point resolution of σ_{point} ~100μm and 200 measured points, the R&D program is indicating that an even better resolution may be possible, so that these goals are not over optimistic.
The general TPC parameters were re-examined by detector studies during the last couple of years: the "Large Detector Concept" (LDC) [13] and the "Global LC Detector" (GLD) concept [14] both of which foresee a TPC as central tracker. The size of the GLD detector was larger and the magnetic field somewhat smaller than for LDC, but otherwise the TPC requirements were similar for both. Meanwhile these two design groups have decided to merge into a single design with the name ILD [15] ("ILC Detector").

3 Magnetic-field issues

To achieve the required tracking performance, systematic effects in the TPC track reconstruction should be corrected to about 30 μm. The symbol σ_0 will be used in the following for this tolerance.

3.1 Systematic uncertainty for the TPC tracking, σ_0

This tolerance is motivated by allowing at most for a 5% increase in the momentum error due to systematic effects for the LCTPC, since a systematic error on the point resolution below about $\sigma_0 \simeq 30$ μm corresponds to a 5% increase in momentum precision (i.e., σ^2_{point}=(100μm)^2+(30μm)^2=(105μm)^2 and $\delta(\frac{1}{p})$ is proportional to σ_{point} in Gluckstern's formula [16]).
As experience from Aleph, which was well understood in 1999, has shown, systematic effects for the TPC could be corrected to the few-10s-of-μm level. This can be seen on p. 58 of [7]. The best possible tracking precision (calculated using the Aleph Monte Carlo) was $\delta(\frac{1}{p}) = 4.5 \cdot 10^{-4}(\mathrm{GeV/c})^{-1}$, For real data, values of $4.6-4.9 \cdot\ 10^{-4}(\mathrm{GeV/c})^{-1}$ could be achieved as year-to-year resolution values after alignment and calibration procedures. This transalated in a 2-to-9% increase with respect to the best possible value. This increase was very acceptable since it did not compromise the physics measurements. The difference in quadrature between best-possible and achieved numbers correspond to a 35-to-70 μm effect [17] which increased the TPC point resolution and can be considered as a measure of the accuracy of systematic corrections.
Using this as a guide and the fact that the LCTPC will have a better σ_{point} and more measured points an accuracy of below about $\sigma_0 \simeq 30$ μm seems to be a reasonable requirement. The final systematic error must however include all corrections [7]: detector alignment due to the push-pull operation, distortions related to background due to space charge and B-field (this note and [2]). The B-field map will correct the magnetic effects while the additional tools, as described in LC-DET-2007-005 [3] (laser calibration system, Z-peak calibration, Z$\rightarrow$ $\mu\mu$ events collected during physics running at energy $\sqrt{s}$, alignment with other subdetectors) will also be used to correct all effects, as was done at Aleph [7].

3.2 Electron drift

The motion of drifting electrons in electric and magnetic fields is governed by the Langevin equation

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

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.
The equations for the movement of drifting electrons due to the magnetic field $\vec{B}$ can be derived from Eq. 1 (see p.16 of [7]) and are the following:

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

and

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

3.3 The B-field map

With the knowledge of the magnetic field components a displacement map for correcting coordinate distortions can be established by using Eqs. 2 and 3. The required accuracy of the knowledege of these field-induced displacements can be directly related with these equations to a measurment accuracy of the magnetic field components or to integrals over the components along the drift path.

3.3.1 The Aleph situation

At LEP, originally the “standard” TPC requirement for B-field uniformity[18] was expressed as the integral

$$\int_{z}^{z_{max}} \frac{B_r}{B_z} dz < 2\text{mm} \tag{4}$$

over the total drift length. The important B-field induced displacement to correct is $\Delta r\varphi$, Eq. 2, because it affects directly the sagitta measurement. Since the component B_φ should normally be zero by design, the remaining correction would be $\Delta r\varphi \simeq \int_{z}^{z_{max}} \frac{1}{\omega\tau}\frac{B_r}{B_z}\, dz$ for $\omega\tau$ large, which was the case for Aleph with $\omega\tau \sim \mathcal{O}(9)$. Thus the ‘2 mm condition’ of Eq. 4 would guarantee a maximal movement of 2mm/9, or $\sim$220μm. However this homongeneity requirement was not enough to eliminate the need for corrections since the Aleph TPC point resolution was $\sim$170μm. *Thus a B-map was still required.* Also the B_φ component had to be measured to determine if it were negligible, which turned out not to be the case; this will be shown in Sec. 3.5.

It is not trivial but possible to design the main LC-detector solenoid which satisfies this ‘2 mm condition’, see e.g. [6, 11, 14]. Nevertheless, as just explained, a requirement on the homogeneity as in Eq. 4 does not guarantee the TPC performance, rather the accuracy of measuring the B-field (in)homogeneity must be specified, as will be done in Sec. 3.4.

3.3.2 The ILC situation

The ILC machine [19] is considering several options for magnetic elements which affect the inner region where the beams pass through the detector and which can affect the B-field in the TPC drift volume. In particular, at the time of Snowmass2005, the linear collider Machine-Detector-Interface (MDI) panel [20] was asking in preparation for the Workshop [1, 21], the following questions, concerning the B field:

- (a) The 14–20-mrad crossing angle geometry requires beam trajectory correction with a Detector Integrated Dipole (DID) as described in LCC-143 [22]. Is this acceptable?
- (b) Overlap of the solenoid field with the final focus quads requires an optics correction with an antisolenoid as described in LCC-142 [23]. Is this acceptable?

In addition, the “anti-DID” was included in (a) as a way to reduce the background due to the outgoing beam in a 14–20 mrad crossing-angle scheme. The questions were posted because these magnets options would influence the B-field homogeneity in the TPC and cause Eq. 4 to be violated.

Meanwhile, the (a) anti-DID has been adopted as a component in the present ILC baseline design, as has been the 14-mrad-crossing angle [19]. Also meanwhile, the (b) antisolenoid stray field has been compensated using a superconducting shield so that its stray-field magnitude is negligible at the TPC.

Therefore the example here is based on the anti-DID.

3.4 The new requirement on the B-field

Since the anti-DID gradient can cause the 2 mm in Eq. 4 to become around 20 mm in the horizontal plane, this 'requirement' on the B-field homogeneity must be relinquished. It will be replaced by a tolerance on the accuracy to which the field map is measured. *In principle if the B-field map is known to infinite precision, its effect can be corrected exactly using Eq. 1. Thus the main question is, to what accuracy must the B-field be mapped so that the corrections allow the momentum resolution to be maintained as outlined in Sec. 3.1?*

It will be important for the LCTPC groups to choose a gas with large $\omega\tau$ so that the drifting electrons follow the magnetic field lines, and minimize the effects of the space charge, which must be corrected using other methods as explained in Sec. 3.1. In the following a large $\omega\tau$ ($\simeq 20$) will be assumed.

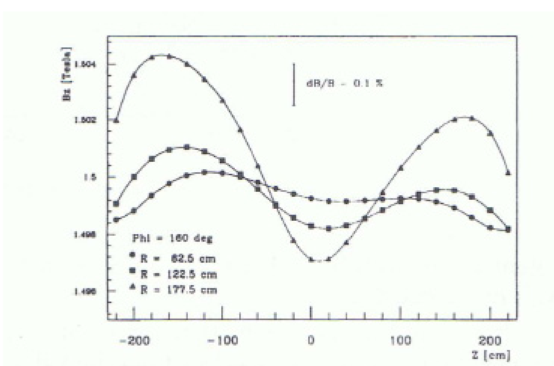
As stated earlier, the momentum resolution for the stiff tracks is directly affected by the $r\varphi$ movement from B-field gradients, Eq. 2. Thus the main requirement proposed here is that the uncertainty on this correction is smaller than σ_0:

$$\delta(\Delta r\varphi) = \frac{(\omega\tau)^2}{1+(\omega\tau)^2}\,\delta\left(\int_z^{z_{max}} \left(\frac{B_\varphi}{B_z} + \frac{1}{\omega\tau}\frac{B_r}{B_z}\right) dz\right) < \sigma_0. \tag{5}$$

In other words, the accuracy of the B-field map must be good enough so that the integral of the field components over the drift paths is known to σ_0 or better. The Δr movement will be described in Sec. 3.5.4.

3.5 Practical example, Aleph

The new requirement will now be compared with the B-field map achieved by Aleph. The measurement of the B_z and B_φ components are seen in Fig. 1. The radial-field



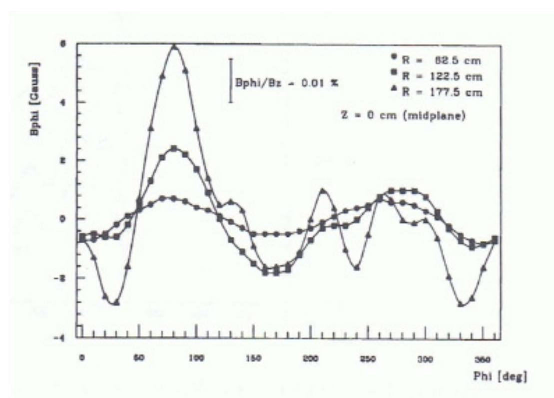


Figure 1: *Left–Fig. II.15 of [18]: B_z field measurements at three different radii. Right–Fig. II.18 of [18]: Azimuthal field measurements at three different radii.*

components and radial-coordinate shifts are shown in Fig. 2 (where it is seen that the '2 mm' condition was satisfied over the entire drift volume). The integral of the azimuthal component is presented in Fig. 3.

3.5.1 The $\Delta(r\varphi)$ displacement due to B_φ

For simplicity only the azimuthal B-field component will be used in the following description of the Aleph measurements for reasons which will become clear below in Sec. 3.5.2, where the radial component will be covered.

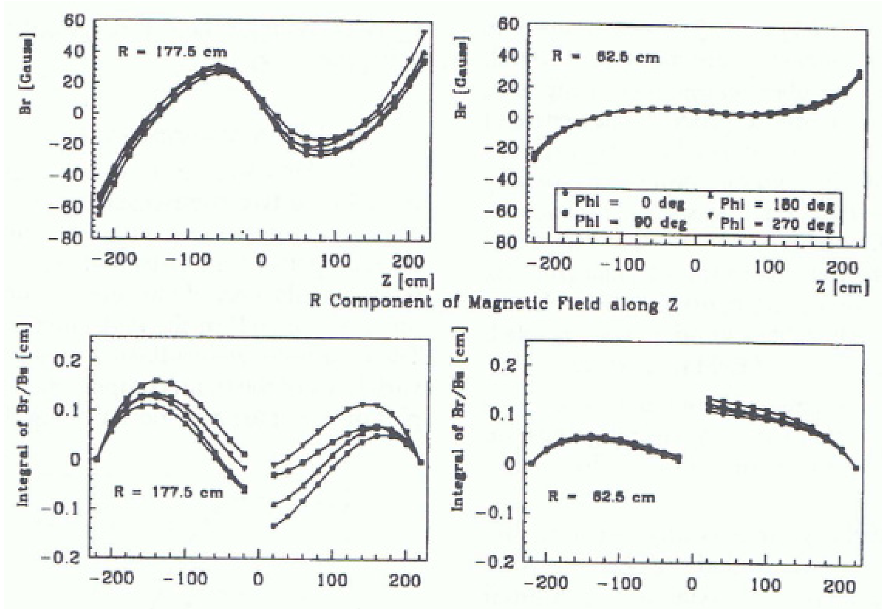


Figure 2: *Fig. II.17 of [18]. Upper: Radial field component. Lower: Line integral of* $\frac{B_r}{B_z}$ *along the z-axis, from z to the nearest TPC endplate, for different azimuthal angles and for two radii.*

For large $\omega\tau$ in Eq. 5 the contribution from the B_φ component to the error on the $r\varphi$-shift of the coordinate is

$$\delta(\Delta r\varphi) = \delta\left(\int_z^{z_{max}} \left(\frac{B_\varphi}{B_z}\right) dz\right)$$

and the error on the integral must be small ($< \sigma_0$). The slope of the line integral in Fig. 3(lower) is proportional to the magnitude of B_φ, and the maximum shift is $\sim$ 0.7 mm (0.1 mm) for large (small) radii which corresponds to 4.5 G (0.75 G) for B_φ. Since the azimuthal component should be small by design, this effect was attributed to the differing permeabilities in the segments of the iron yoke end-caps. These shifts were clearly large compared with $\sigma_{pt} \sim 170\,\mu$m and had to be corrected using the field map. Now for the *main question* from Sec. 3.4: what is the accuracy of such a displacement-map correction? One of the points in Fig. 3 for the movement itself can be approximated by $\Delta r\varphi_i = \sum_{j=1}^{i} \frac{B_{\varphi j}}{B_z} \times \Delta z$, where $\Delta z = z_i/N_i$, N_i being the number of points integrated up to point i. The error in the point $\delta(\Delta r\varphi_i)$ can be calculated by replacing B_{φ_j} by δB_{φ_j} in this expression. In determining the standard deviation $<\delta(\Delta r\varphi_i)\delta(\Delta r\varphi_j)>$ by averaging over the relevant error distributions. For uncorrelated measurements of B_φ one obtains

$$\sigma_{\Delta r\varphi_i} = \frac{1}{\sqrt{N_i}} \frac{\sigma_{B_\varphi}}{B_z} z_i \tag{6}$$

where each of the uncertainites δB_{φ_j} is sampled from the same Gaussian distribution of width σ_{B_φ}.

In principle the error on any of these points can be reduced by using a finer measurement grid. The minimum of the error will be limited by how well the systematic effects of the mapping procedure are under control, how fine the spacing of the measurment grid can be chosen and how well the grid spacing is adapted to the funtional form of the B-field components.

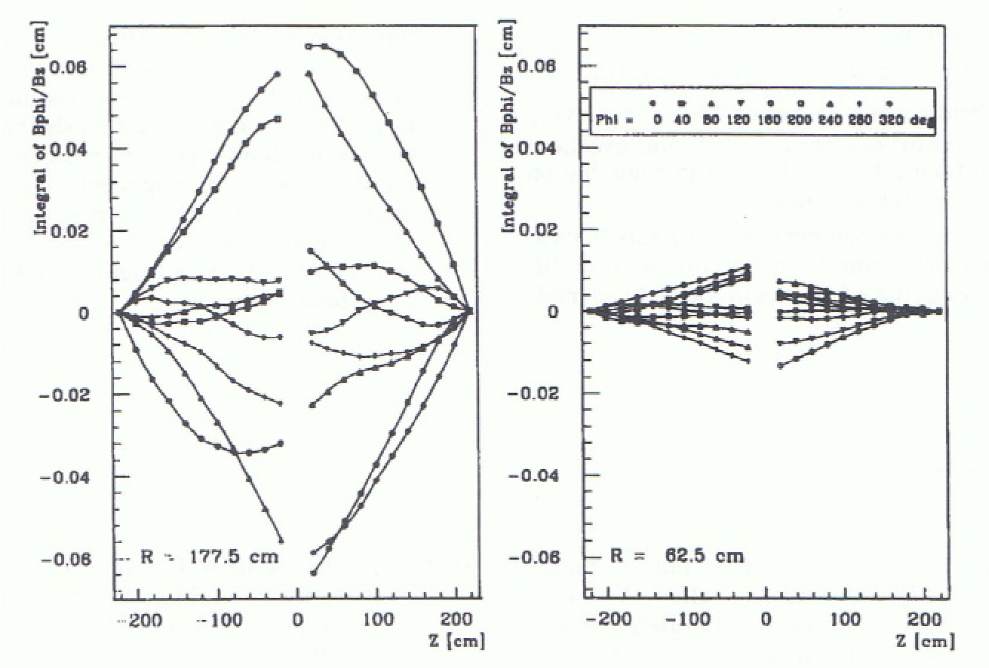


Figure 3: *Fig. II.19 of [18]. Azimuthal-field line integral of* $\frac{B_\varphi}{B_z}$ *measured along the z-axis, from z to the nearest TPC endplate, for different azimuth angles and at two radii.*

It will be shown that the accuracy goals for the Aleph map [24] are sufficient for the LCTPC.
These goals and what actually was achieved will be discussed in Sec. 3.5.3 below, after a short explanation of the B_r contribution to the $\Delta(r\varphi)$ displacement.

3.5.2 The $\Delta(r\varphi)$ displacement due to B_r

The total uncertainty in the $\Delta(r\varphi)$ displacement-correction, due to both B_r and B_φ components which are statistically-independent measurements, is from Eq. 5,

$$\sigma_{\Delta r\varphi_i} = \frac{1}{\sqrt{N_i}} \frac{z_i}{B_z} \sqrt{\sigma^2_{B_\varphi} + \frac{1}{\omega^2\tau^2}\sigma^2_{B_r}}.$$

Since the B_r and B_φ measurements with Hall plates are technically equivalent, the error distributions with widths σ_{B_r} and σ_{B_φ} will be about the same. Thus the B_r contribution will be damped by the $\omega^2\tau^2$ factor and be negligible for large $\omega\tau$. For this reason, only the $\Delta r\varphi$ displacement due to B_φ was used in the previous subsection.

3.5.3 What can be learned from the Aleph B-field map

The goal of Aleph B-map [18] was to measure the transverse field components to $\frac{\sigma_{B_{r-\mathrm{or}-\varphi}}}{B_z} \simeq 1 \times 10^{-4}$, or about 1 G [24]. The difference between measurements and the fit of a model derived from Maxwell's equations [24] was $\sim 0 \pm$'.3' G for B_z, $\sim 12 \pm$'6' G for B_r and $\sim 0 \pm$'6' G for B_φ. The 'errors' are maximal fluctuations δF, not standard deviations. These are close to the goals for Aleph ($\sim$ 1 G) since $\sigma \simeq \delta F/\sqrt{12}$.
For the Aleph example, the residual uncertainty after integrating over the drift distances of the points for a track, Eq. 6 with $N \simeq 11$ for maximum drift (2000 mm), $\sigma_{B_\varphi} \simeq 1$ G

and $B_z = 15000$ G yields $\sigma_{\Delta r\varphi} \simeq 0.04$ mm. The uncertainty is smaller for smaller drift distances.
One issue was that the Hall plates were calibrated to nominally 0.1 G on the test bench, but other effects – fluctuations in positions or calibrations due to temperature drifts, power-supply drifts, etc – were larger than expected so that corrections had to be made on the calibration constants [24]. For this reason, 1 G was assumed for the width σ_{B_φ} in the preceding paragraph.
Although about 1×10^{-4} accuracy was achieved during the mapping, it was not maintained over the long run [18]. For example the configuration setting main-coil↔corrector-coils used for mapping was different from that for data-taking since the compensating power supplies had to be redesigned for operational reasons; also the magnet configuration used during running changed somewhat as the years went by. Therefore it was necessary to develop a B-field model [24] for how to extrapolate to the running configurations for data reconstruction.
The uncertainty due to this procedure could have been reduced if Aleph had taken a few more weeks in 1987 and measured the maps for different main-coil↔correction-coil current ratios and with more points per map (the field was measured at 1.1×10^4 locations over 40 m^3 for one map). The field maps could have been better modelled for interpolation to the running configurations.
Nevertheless, the residual systematics after correcting for both magnetic, using the above techniques, and electrostatic effects, using the additional handles in Sec. 3.1 caused an increase of only 2-to-9% in the momentum error for Aleph as stated earlier. This is also sufficient for the LCTPC, but in future one should be able to do better in order to have more redundancy to guarantee the TPC performance.

3.5.4 The Δr displacement

The Δr displacement is given by Eq. 3, where the rôles of B_φ and B_r are exchanged. The requirement corresponding to Eq. 5, for large $\omega\tau$, becomes

$$\delta(\Delta r) = \delta\left(\int_z^{z_{max}} \left(\frac{B_r}{B_z}\right) dz\right) < \sigma_0'. \tag{7}$$

The B_φ component has been neglected here because, in the case of Aleph, its contribution to this integral was at least a factor of ~ 25 smaller, in the worst case, than B_r due to $\omega\tau$. In the case of the LC detector the situation will be similar. The formula analogous to Eq. 6 for the radial movement and radial field is

$$\sigma_{\Delta r_i} = \frac{1}{\sqrt{N_i}}\frac{\sigma_{B_r}}{B_z} z_i \tag{8}$$

which should be smaller that σ_0'.
The allowed magnitude of σ_0' for the radial movement should be established by simulation. The most stringent assumption that also here $\sigma_0' \sim 30\,\mu$m is the most conservative. The measurement of B_φ and B_r are equivalant from the technical point of view, so that the corresponding Eq. 6 for B_r guarantees that it will be known well enough if B_r is measured to about 1 G.

4 Discussion: the LC detector B-field

The procedure for calibrating the LC detector will be discussed over the next couple of years. Here are first ideas how to approach the B-field for the LCTPC and to profit from the experience gained at Aleph.

- All B-field maps should be mapped so as to satisfy Eqs. 5 and 7 meaning goals of $\frac{\sigma_{B_{r-\mathrm{or}-\varphi}}}{B_z} \simeq 1$ or 2 G as for Aleph. To achieve this the long-term problems that arose with Aleph map must be avoided.

- To improve the accuracy, each map should be made with more points than in the case of Aleph; the number should be determined by simulation; at least a factor of two more z intervals would improve significantly Eqs. 6 and 8.

- The coil should be mapped for many different main-coil settings since it may be necessary to make changes over the years of running.

- Map with several settings of the anti-DID coils (or other MDI magnets), also to cover possible changes during the years.

- The B-mapping gear should be able to measure outside the outer TPC radius and length and down to close to the axis of the magnet.

- A number of tolerances which will affect the overall accuracy must be established by 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.

- Combining all above tolerances, the goal should be to measure the components with a Gaussian of width $\sigma \simeq 1$ or 2 G.

- Mount a matrix of Hall probes on the magnet bore and on the TPC outer surface. The Hall-probe matrix can give a valuable cross-check on the expected B-field at the boundary of the TPC drift volume after everything is assembled and would provide important redundancy if the magnetic-field configuration changes.

- It will be valuable to cross-check the measurements obtained from the different coil-current settings with a numerical simulation of the magnetic field map. The model for the numerical simulation must include effects due to material in the detector, the presence of the yoke, etc. The agreement of the numerical simulation should also be checked against the data from probes on the field cage. In case of a configuration adjustment during operation, when a field mapping is no longer possible, this can provide a valueable crosscheck on the agreement of the real field with the interpolated map from simulations and previous measurements.

5 Next steps

Summarizing, 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 30μm. The answer to the MDI questions in Sec. 3.3.2 on the (a) DID [22] and (b) antisolenoid [23] is that the B-field map for the LCTPC will be good enough to meet the tracking requirements by satisfying Eqs. 5 and 7. The MDI

group is requested to calculate $\int \frac{B_r}{B_z} dz$ and $\int \frac{B_\varphi}{B_z} dz$ the LC detector main-coil+anti-DID for different radii and azimuthal angles.
This note implies that no requirement needs to be placed on the homogeneity of the B-field from the main coil, but rather on its mapping accuracy. Nonetheless some requirement may be warrented for the main-coil homogeneity in order that anti-DID windings provide the proper gradients at the center of the detector. Thus the homogeneity of the main coil is also an MDI issue.
The discussion on this issue will be continuing, and it would be appropriate to iterate via the LC-Note systems http://www-flc.desy.de/lcnotes and http://ilcdoc.linearcollider.org/ to have a reliable way of documenting and following the developments. The tolerances above should be established to better accuracy using realistic simulations which can be reported the same way. Finally, as indicated in footnote 1 on the title page of this note, there are other ways of looking at the B-field requirements for the LC detector; other aspects should also be documented in LC-Notes.

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[13] The European/American 'Large Detector Concept Study' http://www.ilcldc.org

[14] The Asian 'Global Detector Concept Study' http://ilcphys.kek.jp/gld

[15] The ILD concept has written an 'Expression of Interest' to the review bodies of ILC Research Director, and will submit a 'Letter of Intent' in March 2009 and posted on the ILD website http://www.ilcild.org

[16] See p. 274 of the PDG 2004 Particle Physics Booklet. (The complete Review of Particle Physics is published in Physics Letters **B 592** (2004).)

[17] There is a small approximation here to simplify the discussion. These values for the tracking resolution are for all subdetectors (VDET, ITC, TPC) combined. The contribution of the TPC to the overall tracking is estimated here using the experience with Aleph which showed that the overall tracking performance was equivalent to TPC + vertex-constraint. This means replacing 720 by 320 in Glucksterns formula [16] and using L =1.7 m, the distance from the IP to the outside radius of the TPC. Under these assumptions the point resolution of the Aleph TPC corresponds to 179 μm, the value of σ_{pt} used for these estimates of '35-to-70 μm' .

[18] The original uniformity requirement was formulated by J.Rander, LEP Note No.58 (26.11.81) and LEP Note No.65 (December 8, 1981). In [6], it is described in Chapter II, Sec. 2.1, and Chapter II, Sec. 3 contains a description of the B-map.

[19] The GDE (Global Design Effort) submitted the initial design for the complete ILC machine in 2007. This "Reference Design Report" is available at http://www.linearcollider.org/rdr.

[20] At the time of [1], the machine-detector-interface (MDI) work was convened by Philip Bambade, Toshiaki Tauchi and Michael Woods, under the auspices of the

WWSOC, the organizing committee of the World Wide Study of Physics and Detectors for the Linear Collider.

[21] Machine-Detector-Interface Questionnaire for Snowmass 2005
http://www.hep.ucl.ac.uk/~djm/MDIpanelreportJune05.doc
More infomation is available at
http://www-project.slac.stanford.edu/ilc/acceldev/beamdelivery/

[22] B. Parker and A. Seryi, Compensation of the effects of the detector solenoid, LCC-143
http://www-project.slac.stanford.edu/lc/ilc/TechNotes/LCCNotes/PDF/LCC-143.pdf

[23] Y. Nosochkov and A. Seryi, Compensation of detector solenoid effects on the beam size in Linear Collider, LCC-142
http://www-project.slac.stanford.edu/lc/ilc/TechNotes/LCCNotes/PDF/LCC-142.pdf

[24] S. Thorn, An Attempt to Model the ALEPH Magnetic Field, Aleph Note ALEPH 94-162 PHYSIC 94-138.