Detector Requirements at a multi-TeV Linear Collider

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Early thinking towards a detector for a multi-TeV e^+e^- linear collider is reviewed. Several ideas presented here have been generated within the framework of the CLIC studies. The detector must perform well in the e^+e^- range $\sqrt{s} \sim 1-5$ TeV, which will be demanding on the measuring precision and robustness towards backgrounds.

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I. INTRODUCTION

Many reflections for a detector at a future e^+e^- linear collider are strongly influenced by the experience gained at LEP/SLC covering $\sqrt{s}$ up to 0.2 TeV cms energy. The extrapolation for a detector up to 1 TeV, a factor five more than at LEP, is well advanced within the TESLA/JLC/NLC studies (see e.g. [1][2]). TESLA will be used for comparison here. In a nutshell the detector goals are for vertexing $\delta(IP_{r\phi,z}) \leq 5\,\mu\text{m} \oplus \frac{10\,\mu\text{m GeV/c}}{p\sin^{3/2}\theta}$, for tracking $\delta(\frac{1}{p_t}) \leq 5\times10^{-5}(\text{GeV/c})^{-1}$ with systematics $\leq 10\,\mu$m, for energy flow $\frac{\delta E}{E} \simeq 0.35\,\frac{1}{\sqrt{E(\text{GeV})}}$ meaning both electromagnetic and hadron calorimetry must be inside the coil and for hermeticity excellent forward coverage and beam pipe as only (10 mrad) hole in the 4π coverage. To be robust against backgrounds, finest granularity in all subdetectors, minimal material inside the Ecal and a 4T $\vec{B}$-field are envisaged.

CLIC pushes the energy range up by another factor of five relative to TESLA, and the detector question is, "can we still extrapolate from what we learned at LEP/SLC?" We have started thinking towards a detector for CLIC, and an attempt will be made to summarize the issues.

II. SOME CHARACTERISTICS AT $\sqrt{s} \sim$ 3 TEV

These characteristics have been enumerated by Marco Battaglia[3]: events with up to 14 jets, with very high charged and neutral multiplicity, with b-hadrons travelling up to 20cm, boosted events due to beam/brems-strahlung or beam/brems-strahlung-returns, large minijet background, large coherent-pair background and $\sim 2000\ \gamma$s per bunch crossing (BX) passing through the detector.

III. MACHINE-DETECTOR-INTERFACE ISSUES AT CLIC

<u>1-IP $\leftrightarrow$ 2-IP</u>? The CLIC machine group has decided to follow the 1-IP option with a push-pull design for accomodating two detectors.

<u>Which $\sqrt{s}$ for machine-detector studies?</u> There has been a lively discussion about what $\sqrt{s}$ the machine/detector should prepare for. The "low" energy $\sqrt{s} \sim .09 \rightarrow 1$ TeV being proposed for TESLA/JLC/NLC will also be covered by CLIC, especially during the commissioning phase. But that will be at least a decade after TESLA, so the low energy running at CLIC will unlikely be for physics (that is, unless there are some interesting signals from TESLA, JLC or NLC which have to be cross-checked).

One point about low-energy running is definitely indispensable: running at the Z peak for calibrating the detector. This has been in the planning for the $\sqrt{s} \sim .09 \rightarrow 1$ TeV-linear collider for a long time[6], and the technique was recently practiced at LEP2. The luminosity required is modest, about $10^{31}\text{cm}^{-2}\text{s}^{-1}$ would be the minimum needed. This is intimently related to the next paragraph.

<u>Beam delivery system (BDS) at different $\sqrt{s}$?</u> The CLIC BDS is being designed for a $\sqrt{s}$ of 3 TeV and $10^{35}\text{cm}^{-2}\text{s}^{-1}$ luminosity at the moment, and the question to our machine colleagues is, what will be luminosity at the Z peak using this BDS without major changes? If it turns out that $10^{31}\text{cm}^{-2}\text{s}^{-1}$ is not easy, then would definitely be worth rethinking the BDS design to make this function possible. The reason is that ultimately it

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is possible to extend the discovery reach (of any e^+e^- collider) by more than an order of magnitude above the machine $\sqrt{s}$ by looking for deviations of precision measurements from Standard Model predictions of electroweak observables. For this a well calibrated detector as guaranteed by regular data running at the Z peak is essential.

The other issue is how much can we change the $\sqrt{s}$ and keep the CLIC luminosity of $\sim\ 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$? Although it is too early to think of detailed running strategy for CLIC before results from LHC and the low-energy LC are known, it is easily imaginable that running at different $\sqrt{s}$ will be desirable.

Quad stabiliztion? The problem here is that the final beam spots in the experiment have to be stabililized to better than about 10% of the spot size to maintain the luminosity. For CLIC at 3 TeV this translates to 0.1nm[7]. The beams can be steered or the final quadrupoles can be corrected, or both. Feeback techniques for inter-train and intra-train are under study for the 500 GeV collider designs. For TESLA with 337ns between BX, the feedback system is "straight forward", while for the warm machines NLC/JLC and CLIC with 1.4ns and 0.7ns between BX respectively, the implementation is more challenging. Progress in being made[8], and additional techniques such as optical anchor[9][10] will likely be needed for the warm machines.

There are two detector issues related to this point. (1) What is the mechanical tolerance for the final-quad position after all stabilization techniques are applied? (2) These stabilization techiniques must preserve the 4π coverage of the detector, for if they do not, the physics performance will be compromised.

Backgrounds? One important question is whether a gaseous tracker is still viable at 3 TeV. A gaseous system offers the advantage of economical coverage of a large volume with essentially continuous tracking, low material budget and corresponding high quality detector performance[2].

Section II above indicates that the backgrounds will be higher as the $\sqrt{s}$ increases, as to be expected. The main qualitative change in the beam-beam backgrounds at 3 TeV is the large coherent-pair background. But this is at small polar angle θ, while at large angles the 2000 γ /BX passing through the detector mentioned in Section II is a number essentially unchanged from the low energy LC. Therefore it is not excluded that a gaseous system can work at CLIC and improve the performance/coverage/material budget of the tracking system.

The following table summarizes the situation within the context of the beam-beam backgrounds (back-of-the-envelope calculations) derived from [4] for the case of a TPC [5]. The slow TPC seems possible for CLIC since the backgrounds are still much more benign than at LHC.

Some properties related to beam-beam backgrounds.

	TESLA 0.5 TeV	CLIC 3.0 TeV
$N_{e^\pm}$ per bunch ($\times 10^{-10}$)	2.	.4
BX per train	2820	154
Trains per second	5	100
Time between BX (ns)	337	.67
$N_{beamstr.e^\pm}$/BX (θ >150mrad, p_T >20MeV/c)	44	60
Hadr.ev./BX ($E_{\gamma\gamma-c.m.s.}$ ≥5GeV)	.2	4.
Minijet ev./BX (p_T^{min}=3.2GeV/c)	.006	3.4
BX/2ns (e.g. 2-track-timing accuracy of a TPC)	1	3
BX/50μs (e.g. TPC integrating over 2.5m drift)	148	154
Hadr.ev./2ns	.2	12
Hadr.ev./50μs	30	620
Minijet ev./2ns	.006	10
Minijet ev./50μs	.9	520
TPC→Total tracks	40	3300
TPC→Background-track occupancy	.0001	.008
TPC→Converted-γ occupancy	.004	.004
TPC→Total occupancy	.004	.012

IV. DETECTOR ISSUES AT $\sqrt{s} \sim 1-5$ TEV

The answers to the questions from the *point of view of the present author* are the following.

Detector concept S or L? The studies at low energy[1] labelled the options 'S' for small detector with discrete Si-tracking and high $\vec{B}$-field ($5-6$T), and 'L' for large detector with continuous TPC tracking and lower $\vec{B}$-field ($3-4$T). Since L is advantageous for the calorimetry whose effective granularity is increased by moving it further from the IP, it would seem that experiments at multi-TeV are better off with an 'XL' detector.

Energy flow still viable? The energy flow technique was developed at LEP and has been adopted for the JLC/NLC/TESLA detector concepts at low energy. This technique combines the tracking/calorimetry information in an optimal way in order to get the best possible jet-energy resolution. This essentially means that as many details as possible of every event should be measured in order to subtract reliably the doubly-registered energy in the tracking and calorimetry. This works best if the subdetectors have the highest possible granularity.

At CLIC the jets are so dense that this technique *within* jets becomes more and more difficult, the higher the $\sqrt{s}$. However *between* jets the technique should still work well, and this is the largest fraction of the 4π solid angle for most imaginable topolgies. Therefore this technique is also viable for multi-TeV e^+e^-.

Timing? The bunch-time structure is quite different for warm and cold machines as indicated above in the subsection on quad stabilization. This has also been discussed for the low energies[1], and the upshot is that for the subdetectors (not the quad stabilization) it seems not play a major rôle. For a warm machine some (but not all) of the subdetectors should be fast enough to keep up with the BX rate. This may be the mandatory for the forward calorimeters which are fighting much higher backgrounds.

Continuous or descrete tracking? Discrete (Si) tracking has excellent granularity and small σ_{point} but poor dE/dx particle identification and poor V^0 recoginition. Continuous (TPC) tracking makes up for its larger σ_{point} with more measured points, so that the momentum accuary is about the same as for Si-tracking. It measures well dE/dx and the V^0s and presents less material before Ecal, so it will improve the energy-flow measurement: reasons for considering gaseous detectors at energies above 1 TeV (see above about 'backgrounds').

Thus a combination of discrete and continuous tracking would seem best, and moving the gaseous tracking further out is a way to reduce the backgrounds and facilitate the XL detector (see above about 'S or L').

Tracking efficiency important? Clearly it is, and redundancy within the tracking/vertexing is a way to ensure the efficiency remains $\sim$95% at higher energies $>\tilde{1}$ TeV more complicated topologies and higher backgrounds. Another reason for considering combining Si vertexing/tracking with a gaseous tracker at large radius.

Tracking/calorimetry philosophy? This is answered in the paragraph on 'energy-flow' above, and the result is that both systems should have the highest possible granularity. This leads directly to the next issue...

Calorimeter compensation hardware or software? For calorimetry with high granularity it should be possible to combine reliably the electron/hadron components in jets with software compensation, so that hardware compensation is not an essential for the detector design.

Measuring precision of tracking and calorimetry? This issue is not completely cleared up. It seems that the tracking resolution should be roughly a factor five better than at low energy, meaning $\delta(\frac{1}{p_t}) \leq 1 \times 10^{-5}(\mathrm{GeV/c})^{-1}$, while the calorimetry $10\%/\sqrt{E}$ with good granularity is better than, say, $3\%/\sqrt{E}$ with poor granularity.

V. A POSSIBLE LAYOUT

As a result, the layout might look as tabulated below. To repeat, this is the opinion of the present author. Another example using discrete Si tracking can be found in [11].

Radius (cm)	Subdetector	comment
3–15	Vdet	δ(IP)$\sim 10\mu$m
15–80	Silicon/fwd disks	covering$\sim$10m^3
80–230	TPC	covering$\sim$100m^3
240–280	ECAL	30 X_0
280–400	HCAL	6λ
400–450	Coil	4T
450–800	Fe/muon	

[1] World Studies on Physics and Detectors for a Linear Collider, http://hepwww.physics.yale.edu/lc/
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